THE INVESTIGATION OF ARTIFICIALLY ELEVATED TEMPERATURES IN RIVERS AND STREAMS

BY WILLIAM JOHN JOHNSON, PH.D

MAY 1969

DOCTORAL DISSERTATION

SUPPORTED BY

DEPARTMENT OF THE ARMY

GRADUATE FELLOWSHIP PROGRAM

THE INVESTIGATION OF ARTIFICIALLY ELEVATED TEMPERATURES IN RIVERS AND STREAMS

William John Johnson, Ph.D.

The University of Connecticut, 1969

The goal of this research was to supply to the water resource analyst a means by which water temperatures in a river to be subjected to artificial heating can be predicted.

A review of previous research efforts which have contributed to the ultimate goal is followed by a study of the mechanisms of heat transfer acting between stream and atmospheric environments. Based on an energy balance approach, a mathematical model is presented which permits the determination of stream water temperatures from meteorologic and hydrologic input. The model was adjusted to fit data from the White River, a tributary of the Connecticut River, located in Central Vermont. Digital computers were utilized in evaluating effects of various possible patterns of heated discharge and flow augmentation on the natural temperatures.

Other aspects of this broad problem which were discussed include the social, political, and legal aspects and implications of thermal discharge to streams, alternate means of disposing of waste heat, possible constructive uses of waste heat, and monitoring systems and instrumentation for the collection of temperature data.

THE INVESTIGATION OF ARTIFICIALLY-ELEVATED TEMPERATURE IN RIVERS AND STREAMS

William John Johnson, B. S. , M. S.

University of Connecticut, 1965
University of Connecticut, 1967

A Dissertation

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

at

The University of Connecticut

1969

APPROVAL PAGE

Doctor of Philosophy Dissertation

THE INVESTIGATION OF ARTIFICIALLY-ELEVATED TEMPERATURES IN RIVERS AND STREAMS

Presented by

William John Johnson, B.S., M.S.

Major Advisor C. J. Posey

Associate Advisor Victor E. Scottron

Associate Advisor Lewis Leak

The University of Connecticut

1969

PREFACE

The first goal of this research was a review and evaluation of the literature concerned with the study of stream water temperatures.

The second goal was the creation of realistic, practical means of analyzing the temperature of the river environment. A method is suggested for approaching a problem requiring the prediction of the effects of various uses of stream water on its temperature. In this regard, several mathematical techniques were applied which yield valuable insight.

Finally, suggestions were made which, it is believed, will facilitate the establishment of realistic regulation criteria and proper execution of such regulations.

Much appreciation is expressed to Professors C. J. Posey, V. E. Scottron, and W. J. Widmer for their invaluable discussions and patient guidance.

This research was supported by a U. S. Army Corps of Engineers Graduate Fellowship established under regulation ER 690-1-514. Many thanks are due the Corps of Engineers for not only suggesting the dissertation topic but for making available many valuable resources.

Also the valuable assistance of David I. Hellstrom, of the Corps of Engineers, is gratefully acknowledged. His discussion of numerous aspects of the work as well as of computer technology contributed greatly to the successful completion of the research.

Thanks are expressed to William J. Curley, of the Corps, for the fine work on many of the diagrams contained herein and to the typing staff for straightening out some very rough drafts.

Finally, the patient confidence and understanding of the author's wife, Elinor, must be mentioned to complete these acknowledgements.

THE INVESTIGATION OF ARTIFICIALLY-ELEVATED TEMPERATURES IN RIVERS AND STREAMS

William John Johnson, Ph. D.
The University of Connecticut, 1969

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

PAGE

CHAPTER I

GENERAL CONSIDERATIONS

1.1 INTRODUCTION

There has been a growing awareness of a need for engineers to be able to predict quantitatively the effects of engineering structures which affect stream flows or use them in some way. Vitally important at this time is the development of an understanding of the behavior of the river on which such structures are constructed since there is a growing recognition of the fact that interference with one feature of a river's constitution may upset a delicate balance which will subsequently cause changes in others.

Recently, an important quality of stream and river waters has been receiving much attention, that being water temperature. This has been brought about by tremendous industrial growth which has created greater demands for stream waters. The largest demand has been for cooling waters utilized in many industrial processes, consequently resulting in discharges at elevated temperatures. Existing thermal loads discharged to streams are usually of local concern. Such conditions, to mention a few, have been examined in the Mahoning River and Miami River in Ohio; the Tittabawssee River in Michigan, and the Fox River in Illinois and many others more recently. The temperature of many of the Nation's rivers and streams is rising, more noticeably during the summer months of highest temperatures, as a result of increased use of water for cooling purposes by certain industrial operations such as steam electric power plants, steel mills, petroleum refineries and paper mills, all of which must dispose of large quantities of waste heat. (Figures 1.1, 1.2) The most noticeable temperature rises occur during the summer months when natural temperatures are at their highest and stream flows at their lowest. This is not to say that larger rises in temperature do not occur in colder periods, they certainly do, but the consensus is that such increases are beneficial, if moderate. In the ordinary sense of the term "pollution" these cooling and condenser waters are returned to the water course unimpaired in quantity and quality. However, during warm periods, the temperature of the water course may rise substantially above normal levels. This affects the natural waste assimilation capacity of the stream and the normal aquatic life, and may interfere with subsequent downstream uses.

Under natural conditions, in general, the temperature of streams of moderate depth will not be much below the monthly mean air temperature. In the critical summer months of July and August, the water will be within 5 degrees F. above or below the monthly mean air temperature during July and from 3-9 degrees above the monthly mean air temperature in August[1]. As an indication of the problem which is developing it has been found that extreme thermal loadings have caused stream water temperatures to rise as much as 30 degrees F. above the temperature of surrounding air[2]. (Figure 1.3)

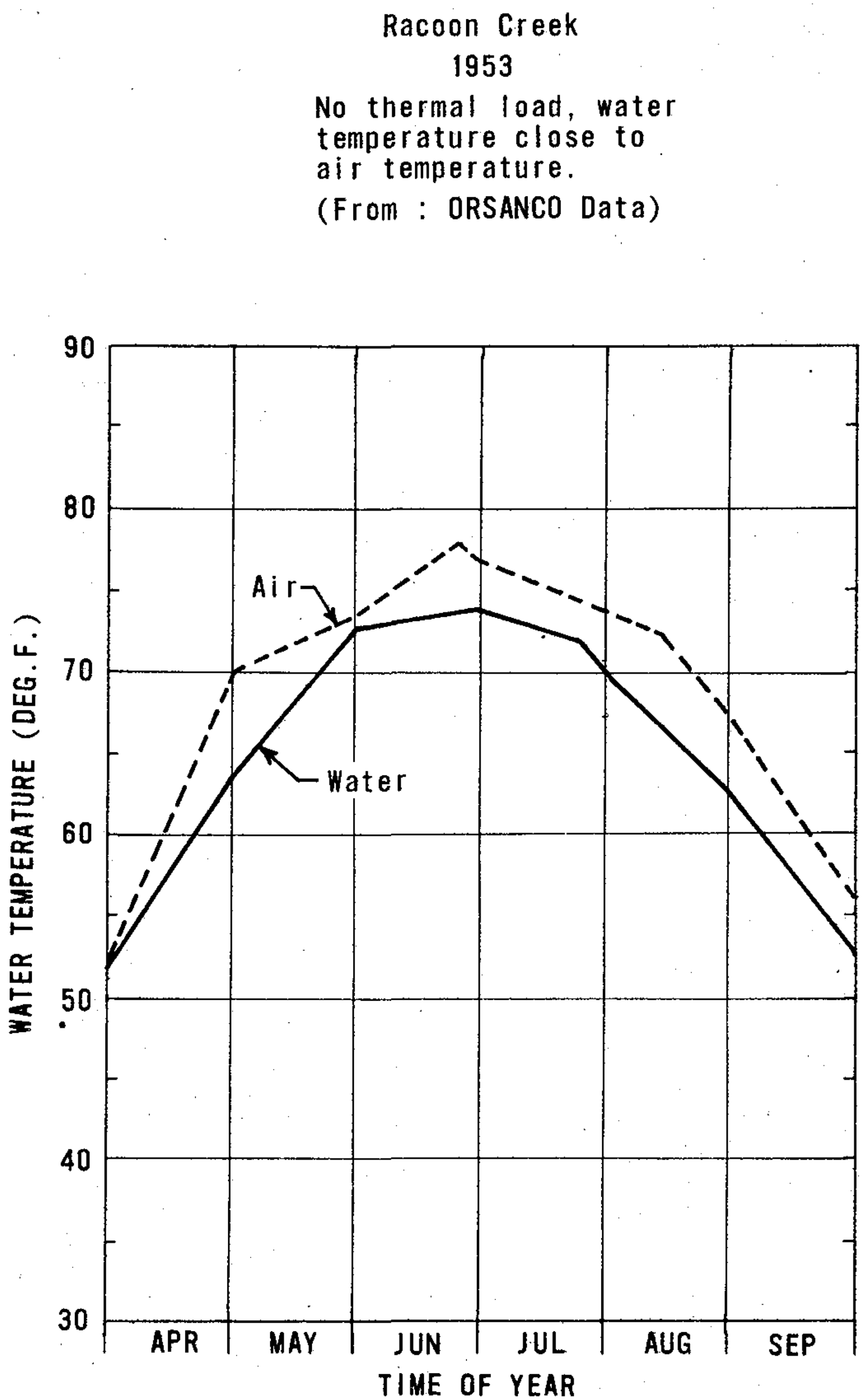


Figure 1.1 Stream Water Temperature Vs. Time of Year, Racoon Creek, 1953

Ohio River

Heavy thermal loading, coping with it in a satisfactory manner. (From : ORSANCO Data)

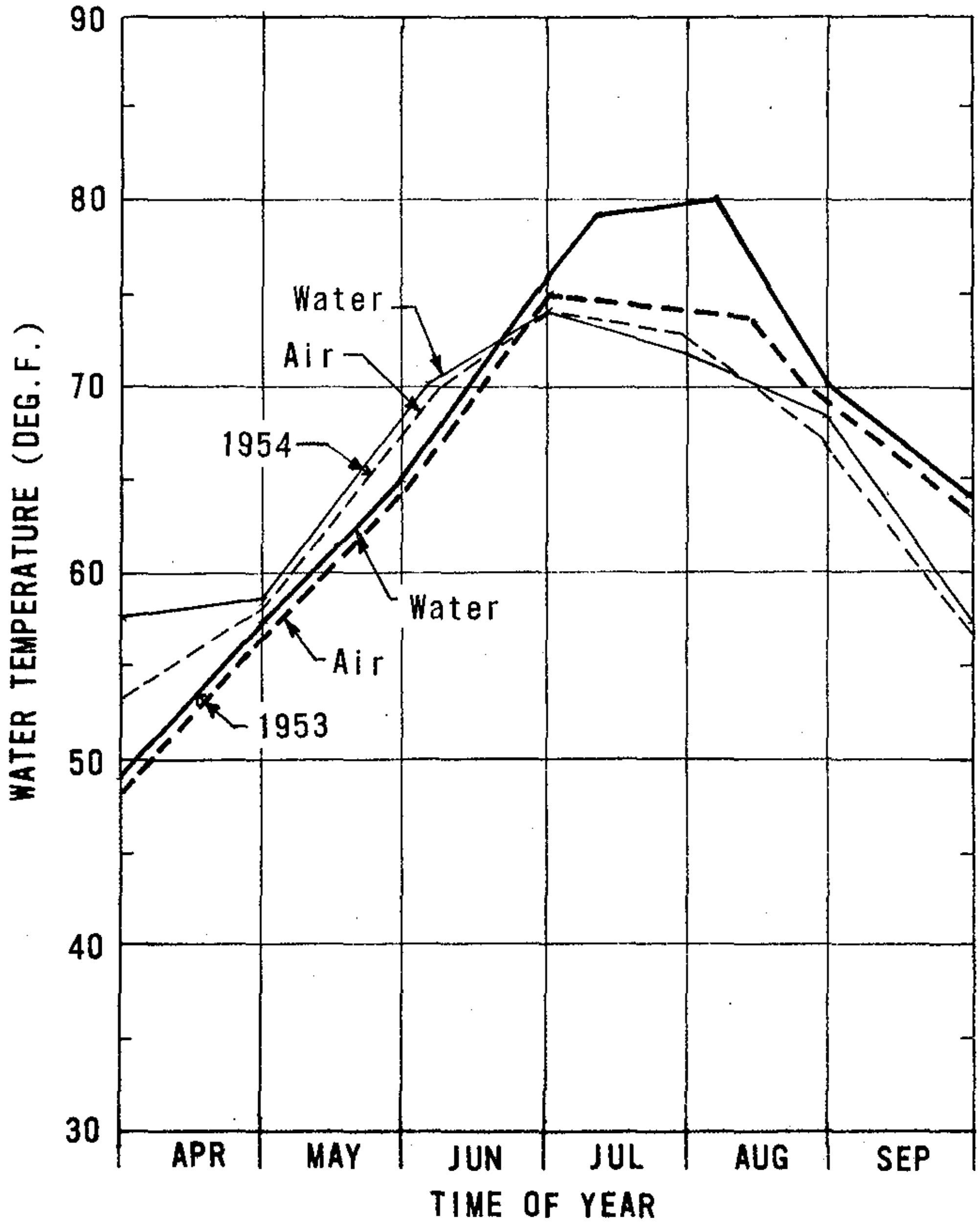


Figure:1.2 Stream Water Temperature Vs. Time of Year, Ohio River, 1953-54

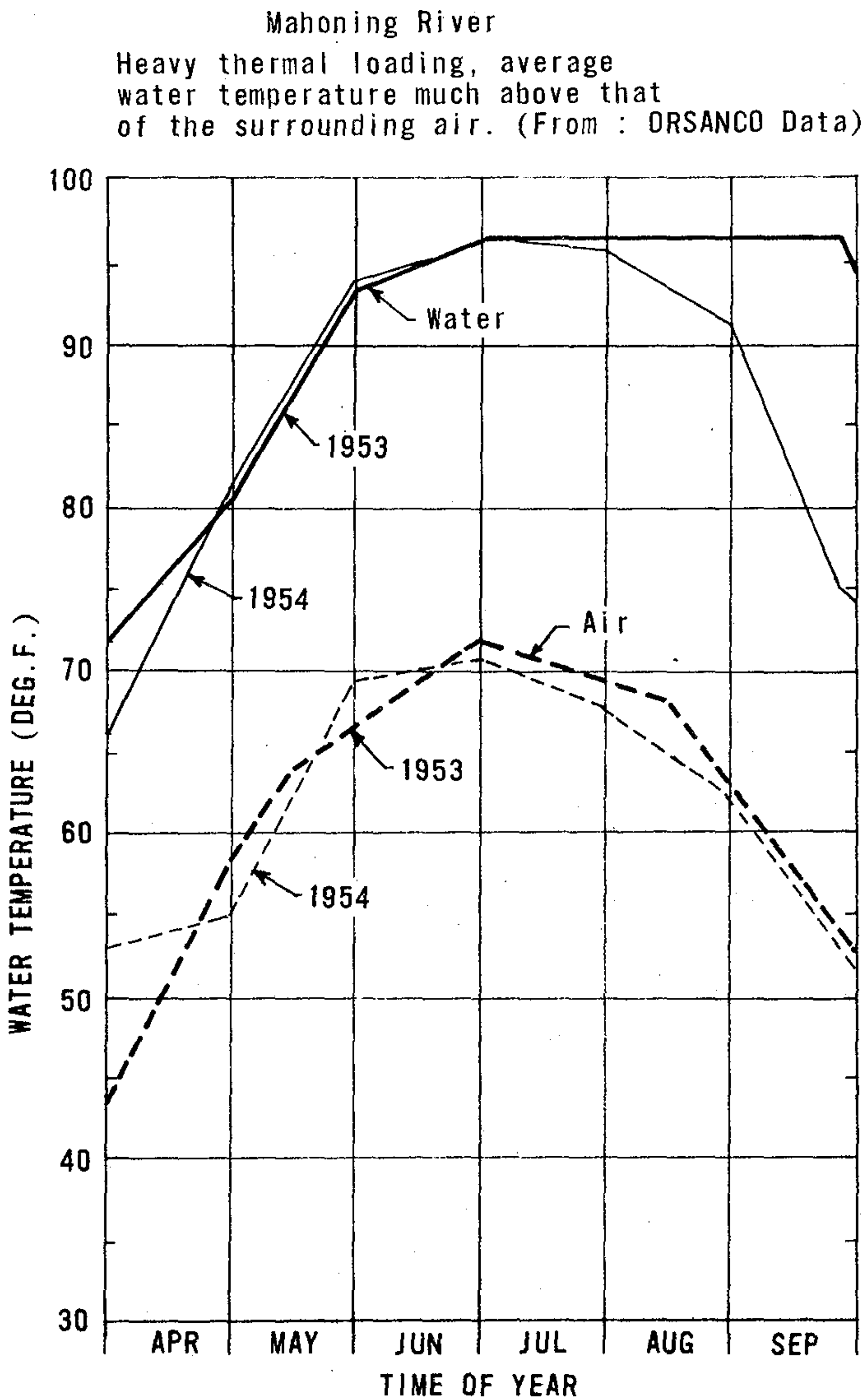


Figure 1.3 Stream Water Temperature Vs. Time of Year, Mahoning River, 1953-54

The earliest concern for the problem was among aquatic biologists. Temperature is a very important factor in the aquatic environment because it can determine the species that will live and reproduce in a given body of water. It governs a number of interdependent water quality characteristics that affect aquatic organisms. Among the important effects of elevated temperatures are changes in viscosity, oxygen content, rate of reaeration and oxygen usage, and chemical toxicity.

Thermal discharges are usually combined with, or in close proximity to, other waste effluents. The result is a more rapid exhaustion of the available oxygen resource of the stream. It is possible to predict the effects of various thermal discharges on the oxygen profile by considering a logarithmic decline in temperature as water progresses downstream. Figure 1.4 illustrates the relation between temperature and dissolved oxygen along a water course. The hypothetical example assumes a mild organic pollutant load is present and that sufficient aeration occurs to oxidize it. Basically, the three curves demonstrate the effect of temperature upon the oxidation rate of the organic load. The relation between thermal load and critical dissolved oxygen content can be developed to ascertain the extent to which thermal loads should be cooled prior to discharge.

There are two related reasons for the current interest in thermal loading. The first, as discussed previously, is the fact that a change in temperature will modify the environment of aquatic flora and fauna

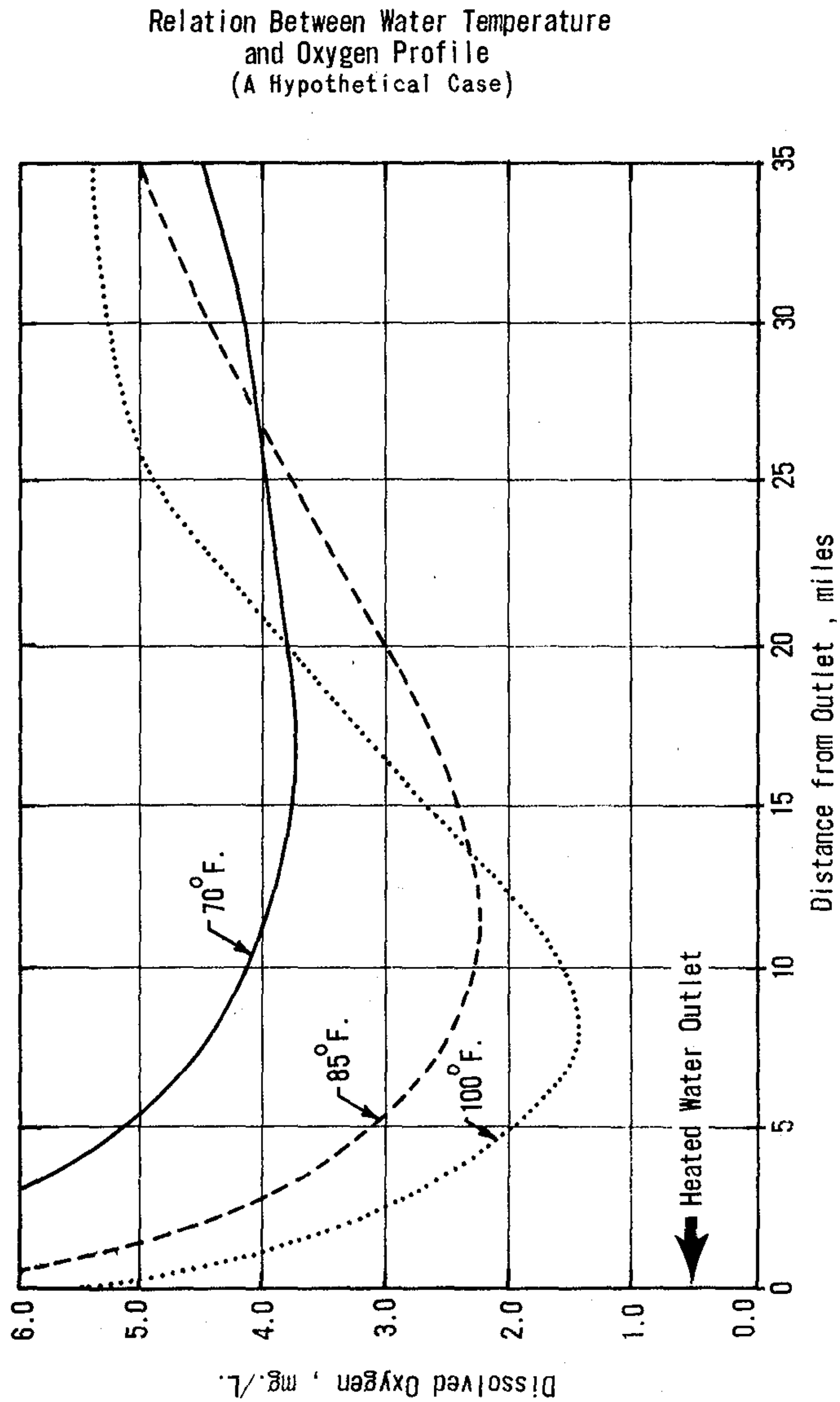


Figure 1.4 Quantative Relationship Between Water Temperature and Oxygen Profile

and thereby cause a change in the species that can live and propagate in a given body of water. The second is a fear that the tendency for thermal loading to increase will in time exceed the capacity of surface water to dissipate the excess heat and thus result in permanent temperature elevations over considerable areas.

There have been, basically, two methods of approach to the problem of determining the distribution of excess heat in a stream. Each has been used with varying degrees of success. It has been recognized that such success is directly related to the extent and accuracy of available data. The approach most often attempted has been what is termed the "heat-budget" method. Here the changes in heat content of a body of water are analyzed by first evaluating the heat transferred by each mechanism separately, (Figure 1.5) and then summing to find the total heat transferred into or out of a specific body of water. (Figure 1.6) There are many practical difficulties encountered in attempting to employ this approach. Variables such as solar and atmospheric radiation, evaporation, conduction and convection are difficult to determine even over short periods of time.

The second method of approaching this problem which avoids the many difficulties of the heat budget type of approach, is based upon the assumption that excess temperatures will decay exponentially with time. Again complete success has been hampered by a lack of temperature survey data.

MECHANISMS OF HEAT TRANSFER ACROSS A WATER SURFACE

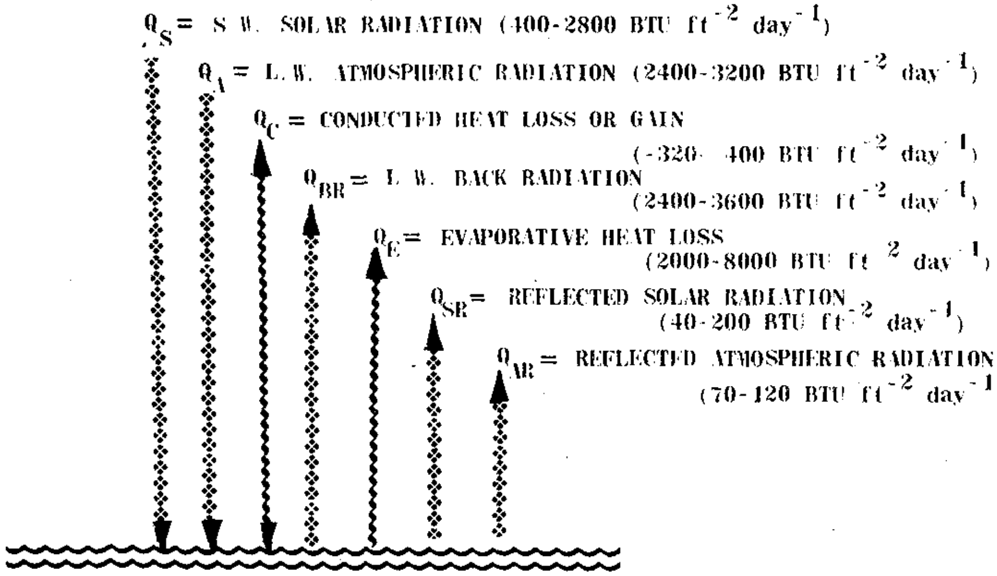


Figure 1.5 Heat Transfer Across a Water Surface

THE BASIC ENERGY BALANCE EQUATION

$$\Delta Q = \underbrace{(Q_S + Q_A - Q_{SR} - Q_{AR})}_{\substack{\text{ABSORBED RADIATION} \\ \text{INDEPENDENT OF TEMPERATURE}}} - \underbrace{(Q_{BR} \pm Q_C + Q_E)}_{\substack{\text{TEMPERATURE} \\ \text{DEPENDENT TERMS}}} \text{ BTU ft}^{-2}\text{ day}^{-1}$$

Q_R

$$Q_{BR} \sim (T_S + 460)^4$$

$$Q_C \sim (T_S - T_A)$$

$$Q_E \sim (e_S - e_A)\,W,$$

e_S & $e_A = f(T)$

W = Wind Speed

Figure 1.6 The Basic Energy Balance Equation

Both of these approaches include further assumption when account is taken of the discharge of the heated effluents. Four conditions may be assumed to exist. (Figure 1. 7) First, if sufficient turbulence exists, the discharge is assumed to mix completely with the total stream flow at the point of discharge. This assumption is usually made because of the difficulty in determining the total length of reach in which complete mixing takes place. The second condition is characterized as vertically stratified. This condition would occur when stream flow is placid and discharge velocities are sufficient to spread the heated effluent over the entire water surface. Immediately, a third condition is established when velocities are only able to spread the effluent over a portion of the surface. This then is both vertically and horizontally stratified.

The fourth, and last, condition occurs when there is channelization of flow with sufficient turbulence to cause mixing vertically. This condition is characterized as horizontally stratified.

There are inherent difficulties of the last two cases. They are concerned with calculating the cooling which results when only a portion of the total streamflow has been heated. This area has received little attention from researchers because, usually, one of the first two conditions is assumed.. Field studies have shown that heat plumes (Fig. 7, Conditions III and IV) do form indicating that concern should be given to cooling water under this condition. Attention will be given to all these possible conditions of mixing in the model to be discussed later.

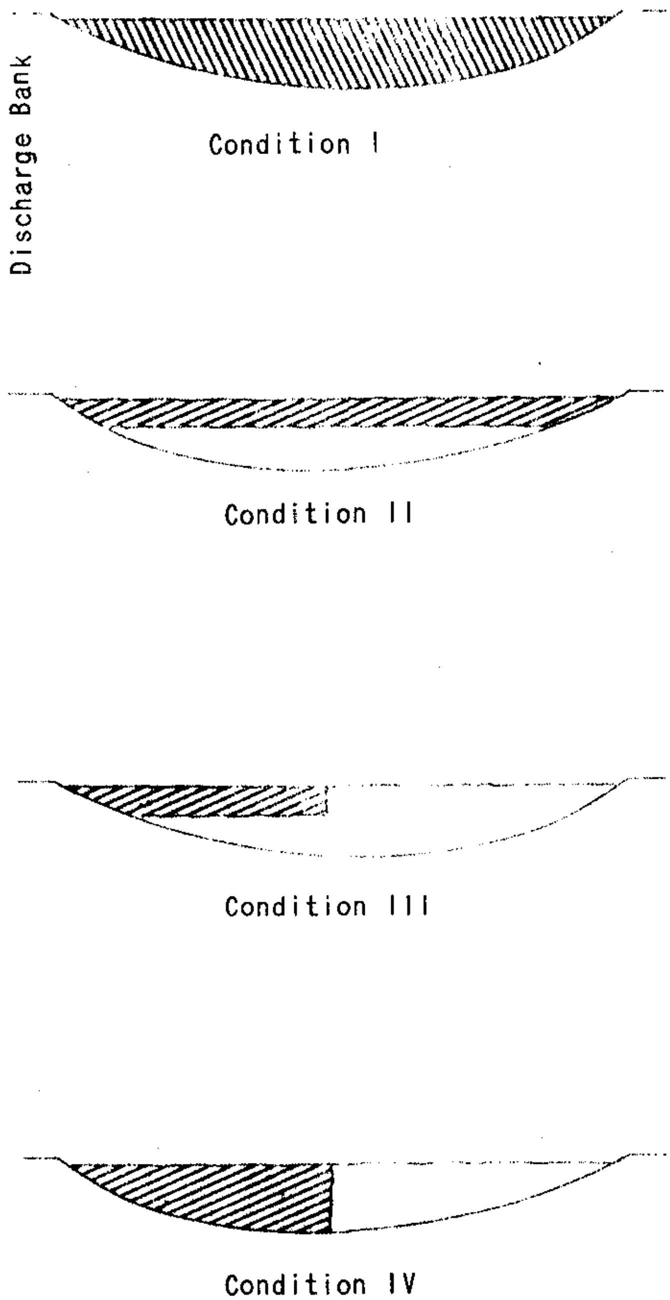


Figure 1.7 Stream Cross-sections showing the Four Possible Stratified Conditions

1.2 THE AIMS OF THIS STUDY

A procedure will be suggested which, hopefully, will aid in the solution of the problem of determining the temperature effect of thermal discharges on rivers and streams. Fundamental to this study is a systematic organization of all efforts which have contributed to the ultimate goal. The mechanisms of heat transfer acting between stream and atmospheric environments will be presented and studied. A review of previous works concerned with heat balances and temperature prediction will be carried out and their contribution to the overall problem will be identified. Suggestions will be made to aid the organization of field surveys with the ultimate goal of supplying data to temperature studies.

Based on much of the foregoing, a mathematical model will be constructed which will determine stream water temperatures from meteorologic and hydrologic input. A case study will be carried out in order to evaluate the mathematical model. High speed electronic digital computers will aid at this point. Simultaneously the simulation technique will be appraised and the applicability of the suggested organization and methodology will be assessed.

Finally a review of the instrumentation available for supervision and maintenance of temperature criteria will be carried out.

1.3 SOCIAL-POLITICAL-LEGAL ASPECTS AND IMPLICATIONS OF THERMAL DISCHARGES TO STREAMS

The ability of many social groups - fishing, out-door recreation, boating, aesthetic conservationists, etc., to place pressure at sensitive locations in order to have their feelings and desires known has often been underestimated. As a result of their concern and interest more effort by science and industry has been directed toward this problem. In the period of time since 1960 there has been a very rapid increase in research and writings concerned with thermal pollution of rivers, the effects of power production on pollution levels, the effects of thermal effluents on stream environments, etc., all of which have created increased awareness on the part of the general public of the potential danger to the nation's waters.

Reactions in many instances have necessitated responsible agencies to set down regulations regarding effluent quality and the use of streams as a heat dump. Such work has been left to the local governing agency and therefore, no pattern has been set which would aid future similar efforts. Of course, most every problem or situation is unique and results in a unique set of regulating criteria. However, the basic approach to analyzing the situation, the areas of concern, and the possible solutions or recommendations are very much similar. A few states have rules governing heated wastewaters. Although these are somewhat vague, they appear to be satisfactory, for present needs at least. The rules will be reviewed in the following pages.

Streams and rivers comprise one of the most important national resources with many uses. Unfortunately, certain uses conflict mildly with others, while some are mutually exclusive. There is universal agreement that the first priority of water use must be assigned to public water supply. The priorities of other uses are difficult to set because of the variation in local interests from area to area. Certainly, one important function is to carry away and assimilate wastewaters. This use is completely accepted and is neither improper nor illegal. However, it is understood that the discharge should not utilize more than a reasonable fraction of the streams capacity for self-purification as necessary to protect downstream uses.

According to R. D. Hoak(3) it is easy to accept this principle of reasonable use of streams because it represents economic logic. Problems do arise, though, when attempting to reach agreement on the reasonableness of a particular use. This difficulty is a direct consequence of limited quantitative information on the actual effects of the different industrial wastes on water quality. Examples of just how limited our knowledge is and how very little factual information is available, occurred when several eastern states concluded that it would be either desirable or necessary to control discharges of heated cooling water. It was quickly discovered that a basis upon which suitable regulations could be drafted could not be furnished.

In an effort, then, to establish a course of action several sets of regulations will be reviewed and discussed.

Noteworthy work leading to the creation of discharge regulations of heated effluents includes the Pennsylvania Department of Health's set of state-wide regulations and the more recent Vermont Water

Water Resources Board Regulations for heated discharges into the Connecticut River at Vernon, Vermont. These two pieces of legislation differ basically in that the Vermont regulations are a refinement of their Pennsylvania counterpart. They refer to specific locations and discharges and could not be easily applied to other areas easily whereas the Pennsylvania regulations are general and intended to be a guide to the development of specific regulations.

The Pennsylvania Department of Health, in anticipation of the future, proposed a set of regulations to govern heated wastewater in 1961. The proposal was advanced to serve as a basis for discussion that would lead to practical temperature controls. The tentative regulations aroused much criticism, especially from industry. The Department of Health, therefore, appointed a committee to study the problem and make appropriate recommendations.

The committee consisted of representatives of both industry and conservation organizations, five of the nine members being engineers. Sub-committees were appointed to investigate particular aspects of the problem, and meetings were held with staff members of the Division of Sanitary Engineering about once a month.

The committee was concerned with a number of areas. First, the problem of establishing a temperature limit was investigated. It was concluded that the maximum allowable stream temperature would be based upon laboratory studies which have fixed lethal maxima for most species of game fish. Of course, the question arose regarding relationship of laboratory results to natural stream conditions. The defending argument presented revolves around the difficulty of accounting for the many variables and that limiting values must be determined under carefully controlled laboratory conditions. In the final analysis, it is proper to select limits suitable to specific local conditions where variables can be estimated by field surveys.

A second area investigated concerned dissolved oxygen. A survey sponsored by Mellon Institute undertook to answer several questions and resolve some misunderstandings regarding amounts of dissolved oxygen present in natural streams and its diurnal variation.

Another area of concern was that the variability of actual stream temperatures. Questions they hoped to answer included: (1) what volume of stream water is affected by a heated discharge? (2) what rates of natural heat dissipation of thermal loads are experienced? (3) what is the possibility of using cool subsurface water for fishways? and (4) are there any tendencies for cumulation of artificial heat in streams? It was apparent that information on these points could only be obtained from field surveys. A number of steel and electric power companies agreed to make temperature surveys. Results of these surveys yielded valuable information and answers to many questions.[3]

Based upon the preliminary regulations and the findings and recommendations of the advisory committee the following regulations for the State of Pennsylvania were promulgated in August 1961 by the Sanitary Water Board.

A. The temperature of the waters of the Commonwealth shall not be increased artificially by amounts that shall be inimical or injurious to the public health or to animal or aquatic life or prevent the use of water for domestic, industrial or recreational purposes.

B. The heat content of discharges shall be limited to an amount that could not raise the temperature of the entire stream at the point of discharge above 93°F assuming complete mixing. The heat content of discharges may be increased or further limited where local conditions would be benefited thereby.

C. Where downstream circumstances warrant, the area in which the temperature may be artificially raised above 93°F will be prescribed.

D. A fishway will be required in streams receiving heated discharges where this is essential for the preservation of migratory pathways of game fish, or for the preservation of important aquatic life.

E. Paragraphs B and C do not apply to streams so impregnated with acid mine drainage that they cannot support a fish population typical of the region except for heated discharges which adversely affect domestic or industrial uses or secondary streams.

F. There shall be no new discharge to waters providing a suitable environment for trout if as a result the temperature of the receiving stream exceeds 58°F.

G. Reduction of the heat content of discharges to estuarial waters will be required where necessary to protect the public interest. Estuarial waters are those containing ocean salts. Tidal waters not containing ocean salts are considered as fresh water streams.

The State of Vermont faced the task of establishing regulations for heated wastewaters when a controversy over the possible environmental effects of a proposed nuclear power plant to be located on the Connecticut River at Vernon, Vermont, erupted and the need for regulation was realized.

In that the waters of the Connecticut River under applicable law, constitute public waters subject to the jurisdiction of the State of Vermont, the burden of creating the regulations was placed with the Vermont Water Resources Board. The Board has the specified duty of providing for the enhancement and improvement of water quality and the prevention, abatement and control of pollution thereof. Many states have established a board or department with such duties.

The Vermont Water Resources Board had earlier adopted Standards of Water Quality applicable to the intrastate waters of Vermont. These standards include certain criteria relating to the temperature of such waters and to the permissible increase in temperature, if any. In that these standards had never been tested previously, the Board was obligated to consider how its standards relating to temperature should be applied.

In order to create additional basis and substance for a set of regulations to govern the discharge at the proposed plant, hearings were held to collect information. Evidence supporting both the pros and cons of such a discharge were heard from knowledgable representatives of the parties concerned. From a consideration of the evidence gathered the Board assembled a list of facts which would form a basis for the regulations to follow. This list was subsequently published and distributed to arouse criticism and discussion. Upon review of the comments received, the proposed regulations were constructed, published, and distributed for comment. Criticisms were considered and a final set of regulations drawn up.

In this particular case the regulations were the central element of an order of permit to the Vermont Yankee Nuclear Power Corporation for the discharge of cooling water and radioactive substances to the Connecticut River. As a result, the evidence heard was peculiar to, for the most part, the reaches which would be effected by the proposed discharge. This is essentially the fundamental difference between the Pennsylvania regulations and Vermont orders mentioned earlier.

The Vermont order placed relatively strict provisions on the Yankee Nuclear plant operation and limited the temperature and volume of its discharge.

There is anticipation of the reintroduction of anadromous fish into the Upper Connecticut River. However, it is commonly known that there are numerous factors or conditions on or in the Connecticut River downstream of Vernon, Vermont, the proposed plant site which are adverse to the reintroduction. Among these conditions are, (1) a high degree of existing pollution from human, industrial and other wastes, (2) the existence of a number of high dams of such height that artificial means will be required to assist such migratory fish, (3) extreme low flow resulting from hydro-power regulation, (4) future pump-storage operation which will also remove water from the Connecticut basin.

Over and above these barriers it was assumed that the reintroduction will be completed and consequently temperature limits are based upon the tolerable limits of the fish. This is reasonable if the likelihood of removing or ameliorating the existing conditions is high. Otherwise it places a greater burden upon the utility.

Certainly, then, this condition should be investigated as fully as possible, as should all parameters which directly influence the temperature criteria.

The Vermont order of permit consists essentially of three parts. One regarding the installation and use of machinery and other equipment as are necessary to cool and otherwise treat the heated water. A second area concerned with temperature rises and rates of temperature rise. In this regard the order states:

> Controlled amounts of heated water may be discharged into the Vernon Pool in accordance with the requirements of the following table, which sets forth in the first column a range of maximum temperatures during any twenty-four (24) hour period as they may occur in the Vernon Pool upstream of the condenser water inlet, and in the second column sets forth the maximum increase in the river's temperature, resulting from such discharges, that will then be permitted during the subsequent twenty-four (24) hour period as measured downstream of the mixing zone:

COLUMN 1 Maximum River Temperature	COLUMN 2 Allowable Increase in Temperature
Above 70°F	0°F
67°F to 70°F	1°F
63°F to 66°F	2°F
59°F to 62°F	3°F
55°F to 58°F	4°F
51°F to 54°F	5°F
47°F to 50°F	6°F
43°F to 46°F	7°F
39°F to 42°F	8°F
36°F to 38°F	9°F
35°F and Below	10°F

> Any discharge of heated water into the mixing zone at Vernon, Vermont, shall be so controlled as not to cause the rate of change with respect to time of the temperature of the river to exceed, upward or downward, one-half of one degree Fahrenheit per hour from May 1 to October 31 and one degree Fahrenheit per hour from November 1 to April 30.

The final area covered by the order concerns the installation and operation of a Comprehensive Monitoring system to measure and record such physical, chemical, and other data as are necessary to ensure that all the requirements of the order are met.

Numerous other cases, which constitute additional steps toward the development of completely successful regulations, might be cited but the two works previously discussed are sufficient to suggest the nature and depth of the problems encountered.

From the preceding discussions, guidelines for the establishment of such regulations may be extracted.

(1) Anticipating the Need for Regulations.

Hopefully, responsible agencies, whether local, state, or federal, will anticipate the future and recognize the need for the regulation of thermal discharges. This is certainly preferable to the creation of regulations only when conditions demand. Anticipating the need will facilitate the establishment of the most comprehensive regulation program possible. With sufficient time to examine proposals, subcommittees may be organized to carry out studies or plan and execute field investigations to supply additional necessary information. In short, foresight will be the most valuable asset to the development of successful regulations.

(2) Supplying information upon which regulations may be based.

If sufficient field data concerning natural stream temperatures, flows, etc. and technical data on existing discharges are available then all that remains to establish a basis for regulations is to determine future demands on the stream and the future of aquatic life contained therein.

(3) Analyzing Information

Thought must be given to the potentials, in terms of industrial and population growth and consequent power need of each area. In other words, an accurate picture of the future demands to be placed upon the stream must be known whether they be for cooling water, water supply, final treatment of wastes or whatever. The presumed necessity for imposing controls over stream temperature as a result of predicted increases in thermal load must be considered with care. Analyses, supported in part by the results of this paper, must be carried out to determine the ultimate potential of the stream to assimilate or dissipate the waste heat. Such analyses will aid decisions regarding the extent to which discharges must be cooled or otherwise treated. For example, based upon all available information we may find that excess temperatures, resulting from waste heat, may have dissipated before another slug of heat is received. Presumably, under these conditions, critical temperatures may never be reached. Of course, individual discharges may cause limiting conditions to be exceeded thereby requiring discharges to be cooled or otherwise treated.

(4) Considering new or improved uses of the stream.

The potentials of the stream as a new or improved fishery must be considered. This was the governing factor in the final Vermont order previously discussed. In this regard, the importance of such decisions must be emphasized. Should a far reaching proposal, calling for the reintroduction of certain types of fish, exist then it is of utmost importance that the reality of such reintroductions be determined. Similarly, the goals of water quality improvement must be considered.

(5) Analyzing proposed regulations.

Tentative regulations should be advanced (a) to serve as a basis for discussion and (b) to arouse constructive criticism. Evaluations may point out areas needing further investigation or suggest areas not previously considered.

1.4 ALTERNATE MEANS OF DISPOSING OF WASTE HEAT

Several obvious facts must be reviewed in order to emphasize that the future direction with regard to the use of the natural environment is quite clear. First, few people are willing to do without electricity in order to return stream environments to their former natural states. In addition, it has been shown that population and industrial growth will continue to proceed at even more rapid rates than in the past. It is clearly understood that this will in turn produce even greater demands for electric power. The result is an ever growing number of electric power generators, with their consequent discharge of waste heat. To avoid further damaging the stream environment future technology must be successful in one of three ways. (1) Produce electricity in a way that there is at least a reduced thermal load being released to the aquatic environment, or (2) find ways to efficiently dissipate the waste heat to the atmosphere, or (3) find ways to constructively use the waste energy. Cootner & Löf[4] concluded that the first alternative is not likely in the forseeable future. The second possible approach will be discussed in this section and the last approach in the following section.

Until recently, power needs did not cause much stress to the surrounding environment and so the waste heat was most economically disposed of by discharging it directly to the stream or other water body. Now that the amounts of waste heat have increased so much, many stream capacities to dissipate the waste heat have or soon will be exceeded.

In some cases, where capacities have been exceeded, with no attempt to curtail further use as a heat dump, the stream environment has been greatly damaged. Ignorance of the situation is probably much to blame. But no longer is this the case. It is understood that some alternative means of disposing of waste heat must be derived. In this regard, a discussion of different methods which have been utilized will be valuable.

1.4.1 COOLING PONDS

One alternative to the use of a stream is the use of a cooling pond. Many reports have indicated successful use of ponds and much theoretical work and analysis have been carried out to aid their design. Of course, a prerequisite to the use of cooling ponds is either the existence of a natural pond or sufficient land area for its construction. Their use may be prohibited if either the land is not available or if it is not the most economical alternative to purchase it.

For many years power plants in water-short areas have depended on ponds and lakes for their entire condensing water supply. Ponds have also served as a buffer between a plant discharge and receiving water.

Several noteworthy contributions dealing with underlying theory, design, and analysis of cooling ponds will be reviewed. One of the earliest reports by D. P. Lima[5] entitled, "Pond Cooling by Surface Evaporation" is an analysis of the behavior of existing ponds. His results permit the prediction of pond temperatures under given conditions. A similar report by N. Lamb[6] entitled, "Power Station Cooling Ponds" delves into the behavior of a pond under varying conditions and ultimately presents performance curves which the author suggests can be used directly for the design of ponds which will be located in areas with similar weather conditions. Still another report entitled "How to Predict Lake Cooling Action" by R. F. Thorne,[7] presents the results of a 25-year study showing how lakes behave under varying heat loads, winds, and air temperature. The three reports here mentioned are probably the best existing aids to future designs. All present very valuable general information to form a basis for preliminary investigations as well as final designs. Typical behavior or design curves, which these works yielded, include those shown in figures 1.8, 1.9, 1.10.

In the paper by Cotter and Lotz[8] concerned with cooling pond design several important considerations necessary to a design are

Surface Loading Vs.
Average Temperature Rise
(From Test Results of N. Lamb)

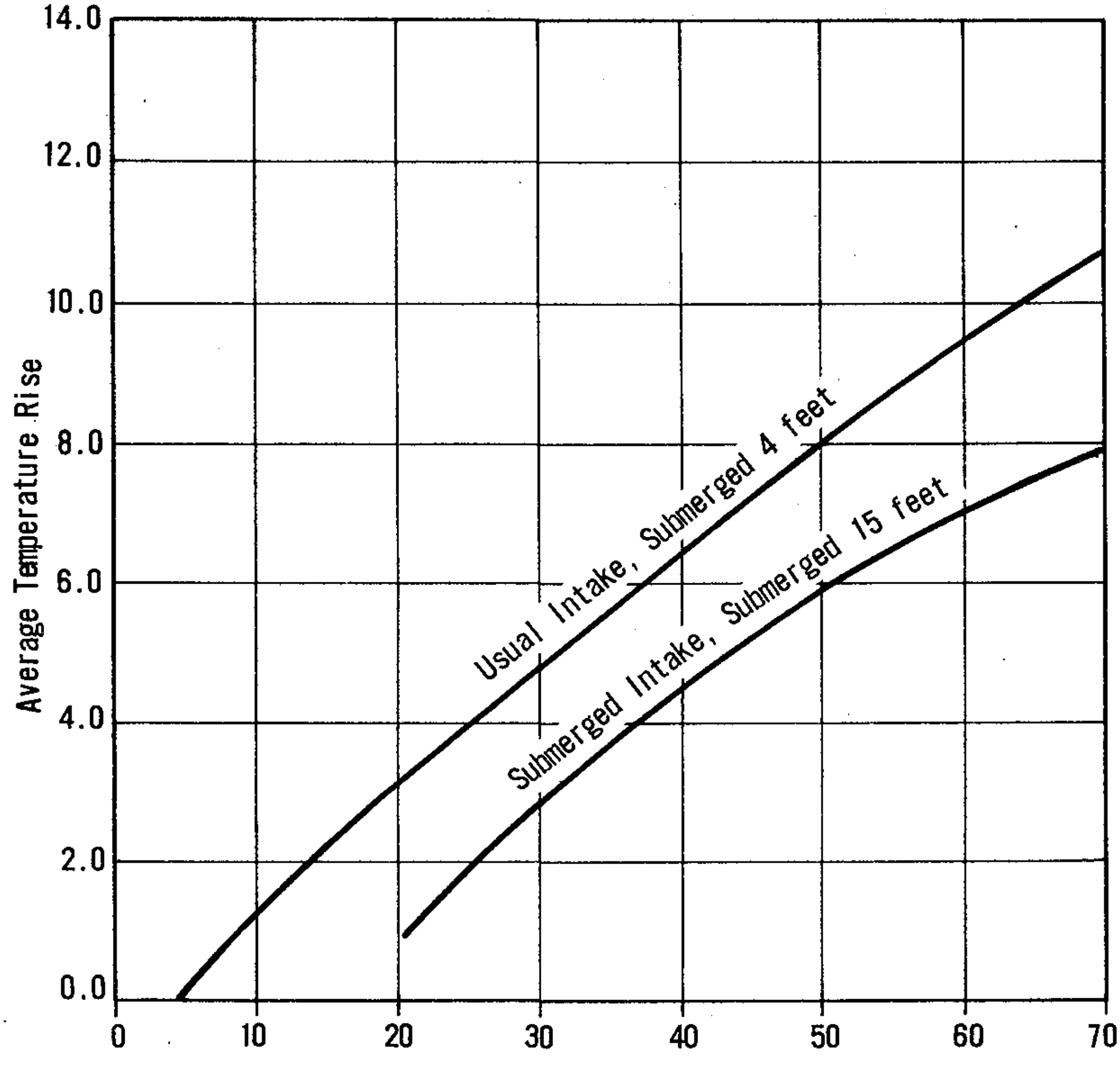


Figure 1.8 Typical Cooling Pond Behavior Curves by Lamb

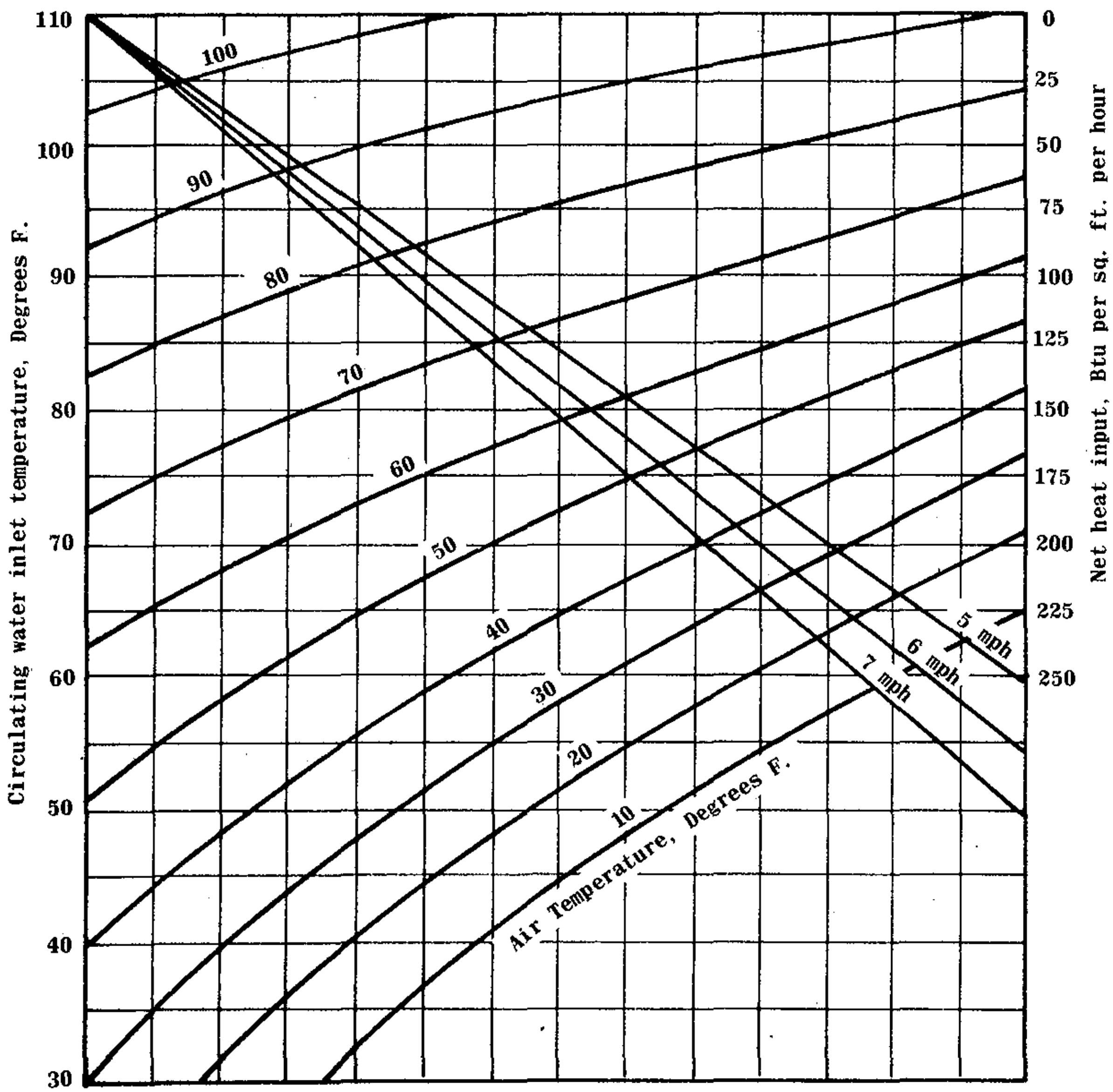


Chart derived by Thorne for figuring heat loadings and temperatures with wind speeds of 5 to 7 mph

Figure 1.9 Typical Cooling Pond behavior Curves by Thorne

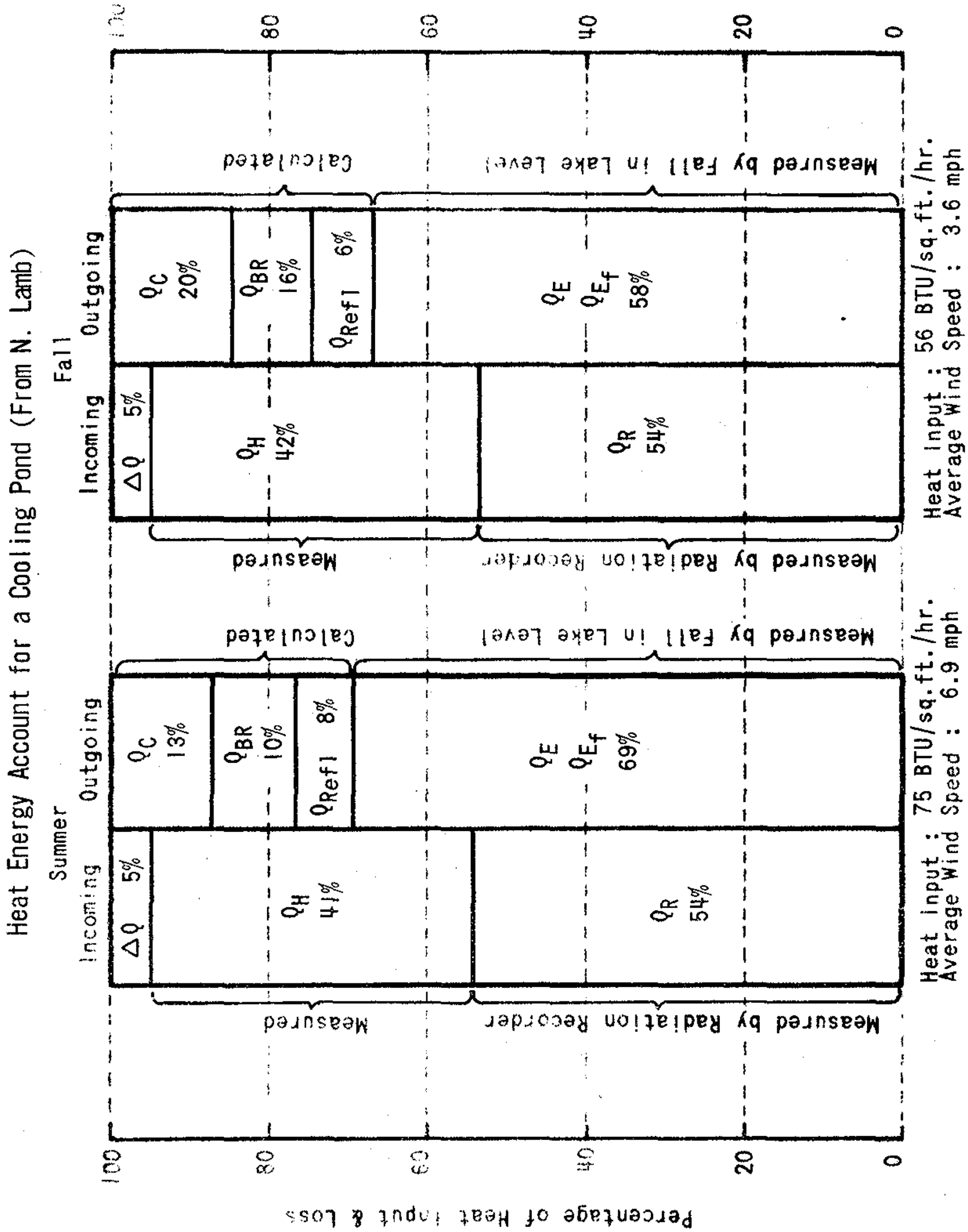


Figure 1.10 Typical Cooling Pond Study Results by Lamb

discussed. These include pond depth, separation of intake and discharge, depth of intake structure and inflow or make-up water supply. Several southwest power plants utilizing cooling ponds are reviewed in light of these design criteria. A conclusion drawn by these writers and one which must be emphasized, is that although many formulas and design aids have been developed for cooling pond design, these can be viewed only as a guide for the estimation of pond size and expected temperature rise. Judgements based on past pond design experience or from careful analysis of designs and resulting performance are invaluable when assessing designs to determine the most efficient.

Another investigation of cooling ponds in general was carried out by Edinger and Geyer.[(9)] Their results are reported in a work entitled "Heat Exchange in the Environment." In review, cooling ponds are classified, on the basis of temperature distribution and circulation pattern. The classifications are (1) completely mixed ponds, (2) flow through ponds, and (3) internally circulating ponds. Characteristics such as pond geometry, location of plant intake and discharge, rate of pumping, and effects of wind mixing all influence the circulations and temperature patterns which may be expected. The completely mixed pond is characterized by a rather uniform temperature throughout the pond and no distinct circulation patterns.

The flow-through ponds are characterized by a condition which may be created either by the geometry of the pond or by a wall system dividing the pond and which requires that the inflow take an extended path to the discharge. Such an arrangement eliminates short circuiting of the inflow and effectively establishes the circulation patterns. There is a definite temperature gradient which parallels the path of flow through the pond.

The internally circulating ponds are characterized by a more complex temperature pattern than is exhibited in either of the first two classes. Basically it is assumed that little or no mixing occurs between the warm lighter surface water from the discharge and the bottom water. In other words, there are two distinct density current flows. A cooling water intake would be so located as to utilize the cooler, density current underflow.

Applying material as developed by Lima, the temperature excess for each of the three classifications is given in terms of pond temperature, T; plant discharge temperature, T_o; equilibrium temperature, E; exchange coefficient, K; pond area, A; and plant discharge rate, Q_p.

For completely mixed ponds:

$$\frac{(T-E)}{(T_o-E)} = \frac{1}{(1+r_1)} \qquad 1.1$$

where:

$$r_1 = \frac{KAQp}{62.4} \qquad 1.1.1$$

for the flow-through pond

$$\frac{(TA-E)}{(T_o-E)} = \frac{1}{(1+r_1)} \qquad 1.2$$

where:

TA = the pond temperature at an area A, square feet from the plant discharge in the general direction of flow.

The basic relation, in the case of the internally circulating pond, is modified to consider the difference in time available for cooling as a function of undetermined interchange between surface and bottom flows. The time available for cooling in a flow-through pond is given by

$$t_c = \frac{V_1}{Q_p} = \frac{A_1 \, d_1}{Q_p} \qquad 1.3$$

where,

t_c = the time available for cooling in the flow through pond

V_1 = mean volume of the pond

Q_p = mean flows rate to and from pond

A_1 = area of pond

d_1 = mean depth of the pond

and for internally circulated pond by

$$t'_c = \frac{m \, A_1 \, d_1}{Q_p} \qquad 1.4$$

where,

t'_c = the time available for cooling in the internally circulating pond

m = some fraction of the mean depth occupied by the outflow from the plant

A_1, d_1, Q_p as previously defined.

The results of this work when used in conjunction with the previous works mentioned, will supply a very effective means of designing cooling ponds either as a main source of condenser water or as a buffer between plant discharge and receiving water.

1.4.2 COOLING TOWERS

A second alternative is the use cooling towers which again may be the prime source of condenser water or only a buffer between plant discharge and receiving water.

The application of cooling towers, until recently, has been confined to those installations inaccessible to rivers or other large bodies of water. Now, in light of the strained thermal conditions which are found to exist in many streams of the Eastern United States, and recognizing that in this same area cooling ponds are not a feasible solution, the cooling tower has become one of the only means remaining which will successfully combat thermal pollution. Also encouraging further use of cooling towers has been the fact that they are economically attractive when considering high site costs, heavy transmission-line charges, and increased fuel transportation costs. The earliest industrial cooling tower employed widely was the natural draft tower. This type relies on natural circulation of air, the cooling medium. The towers are comparatively tall structures, resulting in high pumping costs of circulating water. Water loss is high, requiring continual make-up and often created considerable maintenance on surrounding equipment. Further, performance of the early towers was entirely dependent upon wind and atmospheric conditions.

Forced draft or mechanical draft towers, on the other hand, pass air at a known rate, facilitating better performance prediction. The structure is much smaller thus reducing pumping costs but now fan operation costs must be included.

Finally, the induced-draft tower was developed which consisted basically of a large-diameter fan of high capacity located above the circulating water section. This system afforded better control and performance but is found to be more expensive to operate due to several facts. It is now required to pump hot air rather than cold, in other words, greater volumes of air are moved, and the mechanical equipment is less accessible.

In the past few years, the hyperbolic natural draft cooling tower has gained prominence in the field, replacing the mechanical draft tower. This type is well known in many European countries, while it was not until 1962 that the U.S. saw its first. The most obvious objection to the tower is its cost, both capital costs and increased plant operating costs. A typical natural draft "wet" tower for a 1000 MW nuclear unit may cost up to $10 million, according to Richards.[10] In spite of this, the British Electric Authority has installed a large number of such towers in stations throughout England. E.E. Goitein[11] sights many factors which make this design attractive.

Other objections may rise out of tower appearance and size. Although esthetically proportioned, they may be as large as 370 feet high and 380 feet in diameter, as are the towers for the Fort Martin Station of the Allegheny Power System, the largest in the world.

The final major objection to cooling towers is the fog problem which can be undesirable in many areas under certain humidity conditions.

Under appropriate conditions a vapor plume rising several hundred feet above the top of the tower and miles in length could cause hazardous conditions upon falling and freezing. A. D. Converse[12], in an investigation of possible fog conditions which could be expected to exist at the Vernon, Vermont Nuclear Plant site, presents a good method for approaching such an analysis.

In spite of these many objections the use of hyperbolic natural draft cooling towers is gaining momentum, because, basically, it is the most economical to operate.

A very comprehensive presentation regarding the selection and application of cooling towers is mady by Goitein. The paper is intended to assist those who are finding it necessary to employ cooling facilities for the first time. General considerations, guides and examples are presented which will now be reviewed.

According to Goitein the paper has a twofold purpose.

(1) To discuss the more important factors concerning the economic application of cooling towers in steam power plants.

(2) To discuss the selection of the cooling tower for a given set of plant requirements.

In a majority of cases the cooling tower is employed when an existing generating station is expanded and the water flow in the river is not sufficient to provide the necessary condenser circulating water during the summer months. Expanding an existing station is in many instances more economical than building a new generating station at a new site whose only advantage is the availability of a natural source of circulating water.

Gausmann[13] discusses many of the aspects to be considered in balancing the feasibility of expanding an existing station located on a river by providing a cooling tower for summer service versus building a new station on another river location.

For a new plant on a new site the considerations included:

(a) Basic capital cost

(b) Increasing the transmission line length

(c) Possible higher fuel costs.

while considerations on adding to an existing facility include:

(a) Use of existing facilities

(b) Partial use of existing fuel handling facilities

(c) Use of existing land for plant and transmission right of way

(d) Partial use of transmission facilities

(e) Limiting supervisory and maintenance personnel

(f) Elimination of any increase in transmission losses.

Goitein discusses further the fundamental economic aspects and variables for obtaining the optimum cooling tower size. Also, design requirements are established and the Cooling Tower Institute specifications are reviewed. The last section of his paper is dedicated to the determination of tower size. Included are many design curves and equations necessary to determine the characteristics of the optimum tower.

Schematic diagrams of the different towers discussed are shown in Figures 1.11, 1.12, 1.13, 1.14.

1.4.3 FLOW AUGMENTATION

Another way by which the effects of artificial heat discharges to streams may be abated is that of reregulating flows to facilitate augmentation during periods of natural low flow and high temperature. It is assumed that increased river flows at these times will reduce temperature locally by dilution, to the benefit of temperatures in the other downstream reaches.

The basic function of reservoirs has usually been to regulate flows in a basin for the purposes of flood control, municipal and industrial water supply, fish and wildlife enhancement, recreation, or water quality control. It has been recognized, now, that a possible additional function of any proposed development is the control and enhancement of stream water temperatures. This is, of course, a result, in part, of the new understanding of the temperature as an important water quality parameter.

An essential part of a comprehensive study now being undertaken for the development of the Connecticut River Basin's water resources is an understanding of the temperature environment. Central to the

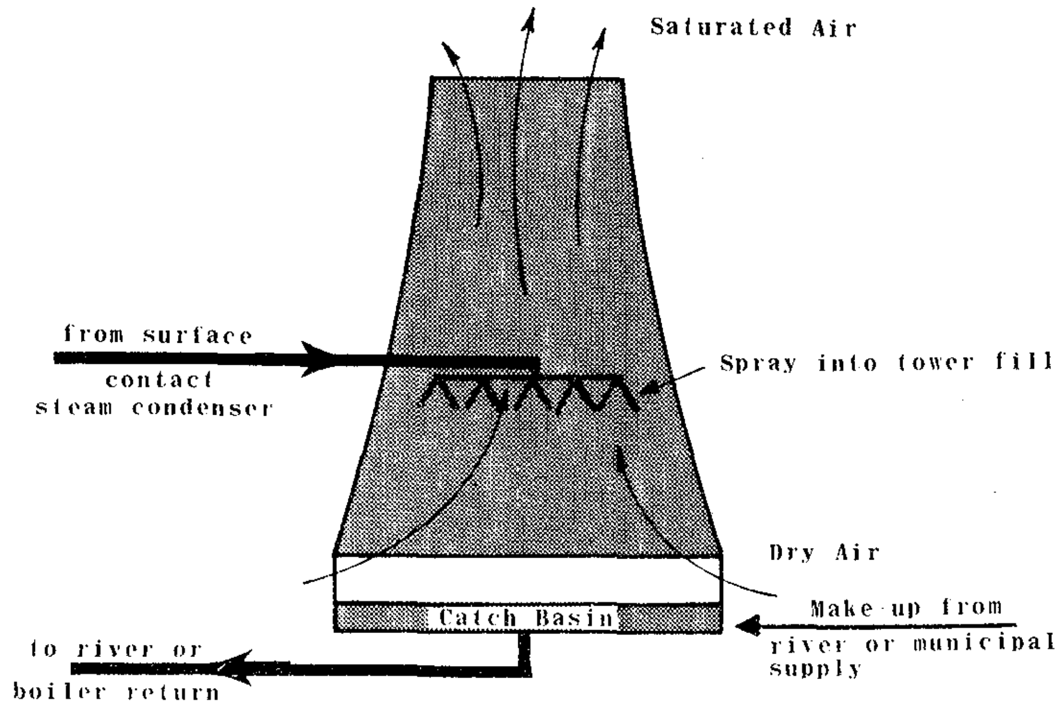


Figure 1.11 The Natural Draft Wet, Open or Evaporative Cooling Tower

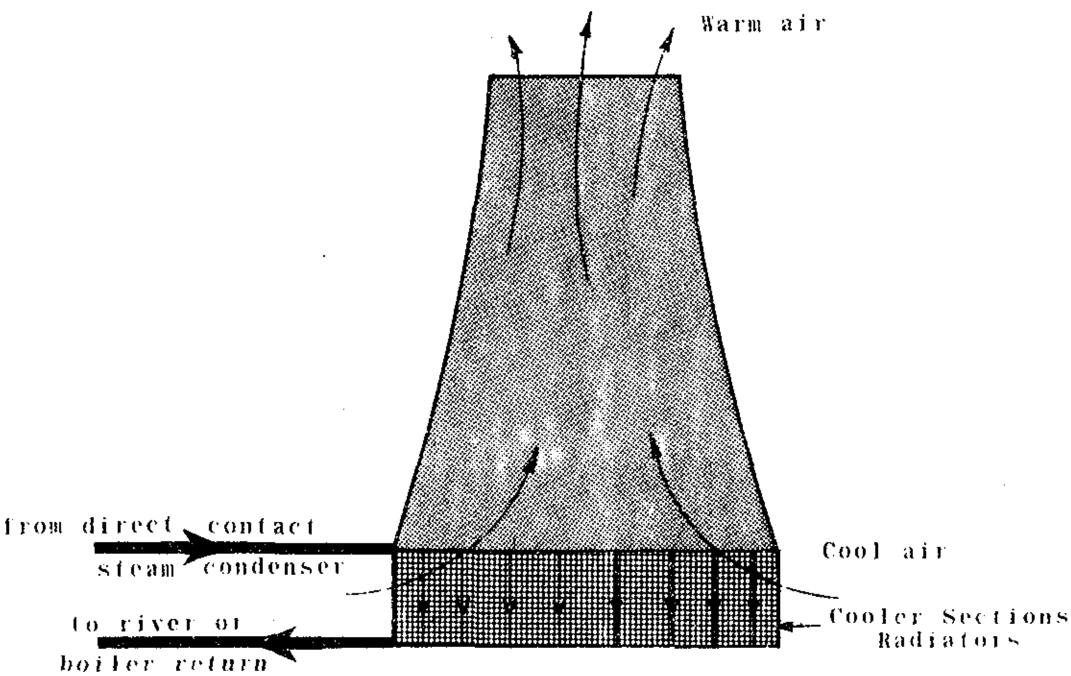
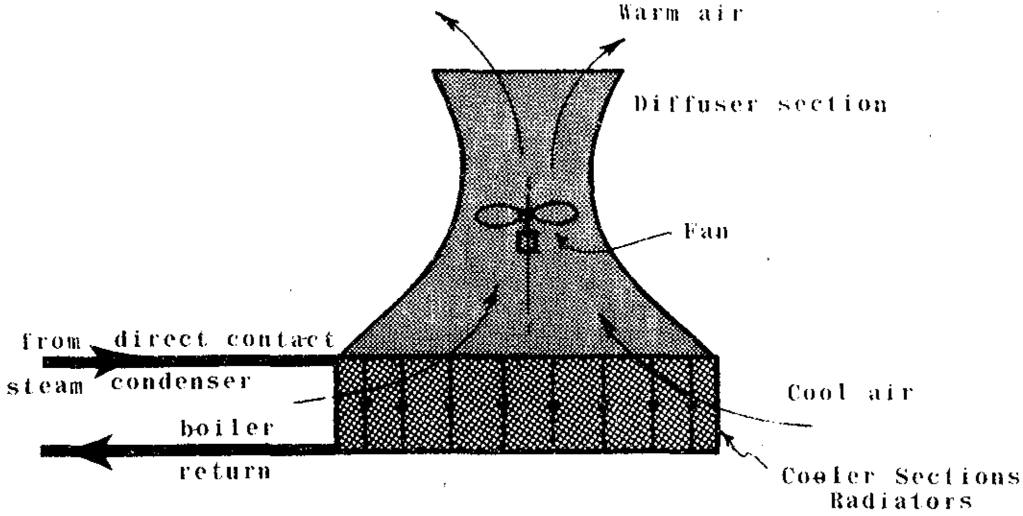
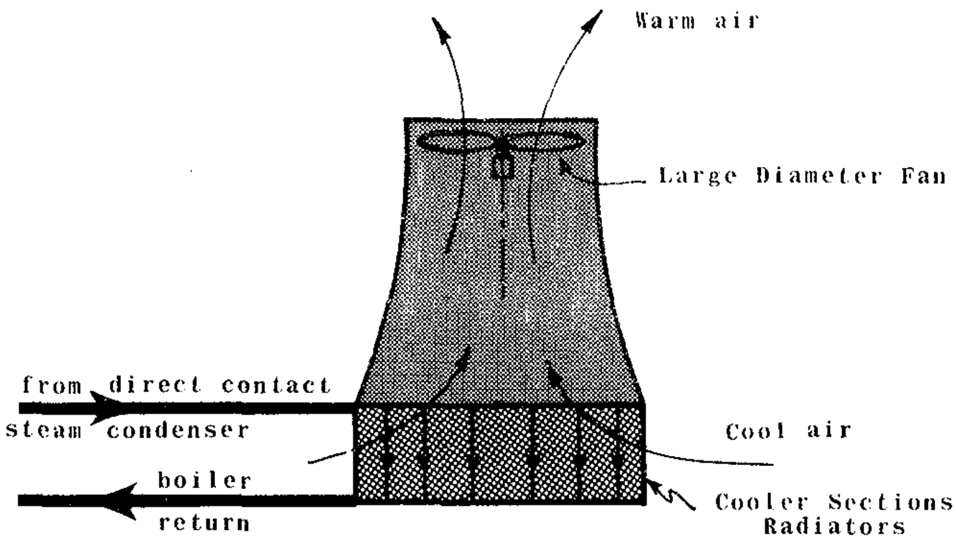


Figure 1.12 The Natural Draft Dry or Closed Cooling Tower



Forced Draft Dry Cooling Tower

Figure 1.13 The Force Draft Cooling Tower



Induced Draft Dry Cooling Tower

Figure 1.14 The Induced Draft Cooling Tower plan of development envisioned by the U. S. Army, Corps of Engineers, the agency responsible for the study, are numerous reservoirs to be located on major tributaries. In just what way these reservoirs are capable of influencing and controlling downstream temperatures, if they can at all, cannot be determined without a specific investigation of the proposed facilities and the river basin, in general. To date no method has been derived for the design of reservoir systems to optimize their effects on temperature and to meet predetermined temperature limits in downstream reaches. The only work of help in this regard has been the analysis of existing reservoirs and their effect on downstream temperatures.

Several good discussions regarding the effect of run-of-the-river impoundments are available.

Jaske and Goebel[14] present the results of a study which attempts to analyze the effect of dam construction on temperatures of the Columbia River. To establish a datum they analyzed U. S. G. S. temperature data for the period October 1933 - October 1954 using routine statistical methods. An essential need stressed in this paper and similarly emphasized by this writer, is for reliable data, without which all work must be viewed with caution. In this regard they suggest that a national standard for the reporting of temperature data can be established possibly under the direction of such organizations as the AWWA or the USGS.

Their conclusions indicate that the erection of low-head reservoirs did not produce significant change in the average temperature of the river, however, they did decrease expected variance in the water temperatures. In certain locations, however, it was noted that releases lowered temperatures by as much as 2 to almost 4 degrees F. Other studies by Jaske on the Columbia concluded, that the overall effect of impoundments on the main stream caused increases in temperature estimated to be from 1 to 3 degrees F. for each major structure. Obviously, there is not much consistency of opinion, indicating that the results of studies are needed.

Another report by Churchill[15] reviews the effects of TVA storage reservoirs on downstream temperatures in the Clinch River, a tributary of the Tennessee River. Numerous water temperature profiles are presented which vividly describe the effects of reservoirs. His conclusions indicate that the impoundments have a definite effect upon stream water temperatures. Significantly large reductions in mean stream water temperature with accompanying reductions in variance are reported.

These studies have only been possible when data describing temperature regimes before reservoir construction were available, and have indicated that a very desirable result is possible. For example, Churchill found that if water is released through low-level outlets in a dam, significant effects on downstream water temperatures result during the summer months. His paper presents data observed in, and downstream from, these impoundments that have been collected over a period of approximately 26 years.

Similarly, in the Columbia River studies it was concluded that the temperature may be regulated successfully by the proper operation of the reservoirs.

It is often difficult to apply findings of such studies to other areas because, as reminded by Jaske, there is danger of excessive generalizations. All too often there is a tendency to take the experience of one particular region and to immediately apply it to any situation. As an example of the dangers existing, Northwest studies have concluded that reservoirs constructed on streams tend to raise the overall mean temperature while in the Southeast temperatures are lowered. With this in mind, it might be concluded that there is then, no information which would directly apply to the Northeast area because no studies have been carried out. Consequently, until such data is collected which is applicable, attempts to evaluate reservoir effects must be based upon assumption or estimation.

The results of this investigation when used in conjunction with work presently being carried out on reservoir stratification (by Harleman and others) will yield methods which will enable the complete analysis of temperatures of river systems. For, once an understanding of thermal stratification in reservoirs is at hand, outlet works can be properly located to take advantage of the coolest waters. This will ultimately lead to the capability of predicting discharge temperatures. When these methods are used together with techniques being simultaneously developed to predict the change in temperature in downstream reaches, then the needs of design and analytic methodology will have been fulfilled.

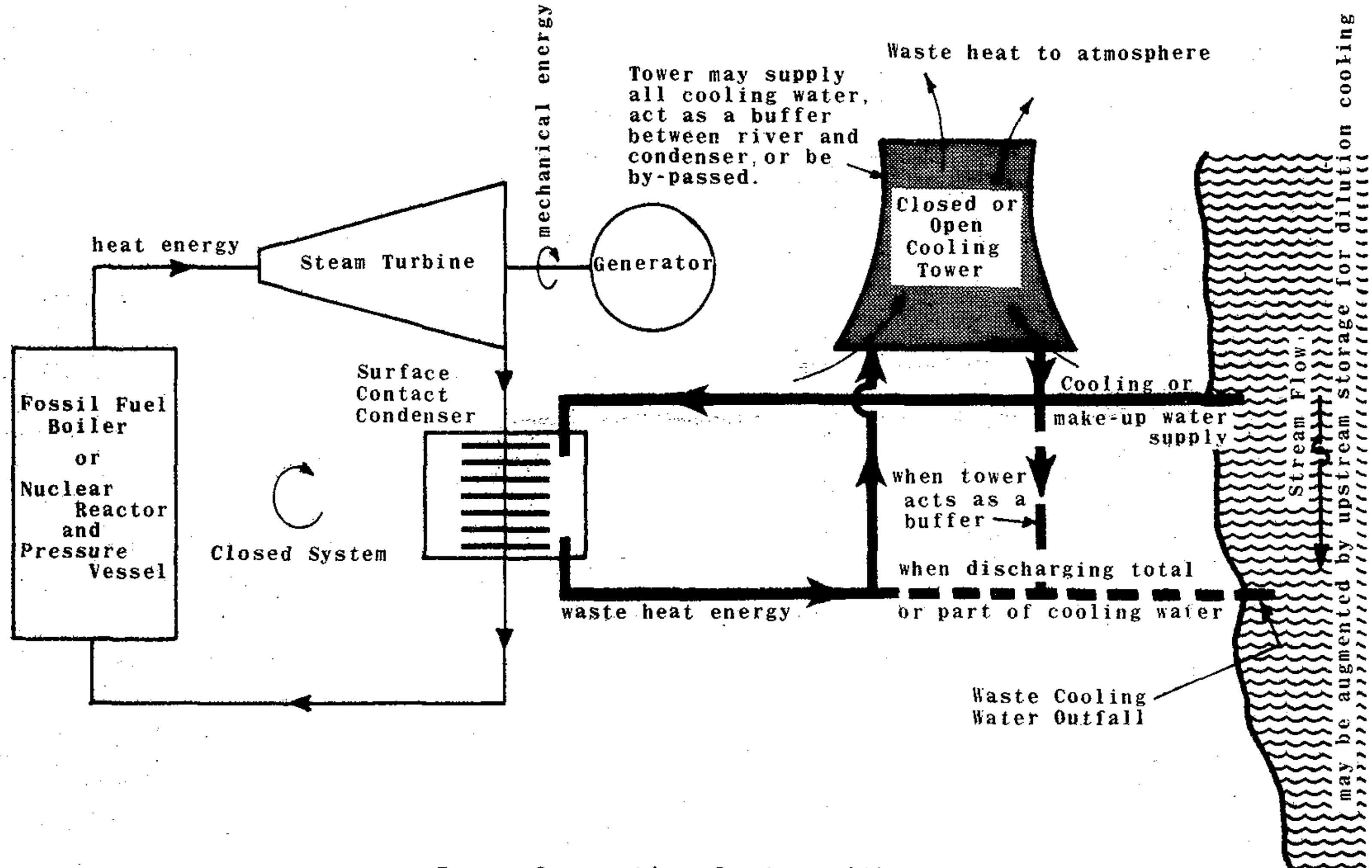
1.4.4 HYBRID COOLING SYSTEMS

Probably the most economical and efficient means of disposing of waste heat is through the use of hybrid cooling systems. Basically, such a system is made up of several or all of the methods previously reviewed, e.g., cooling ponds, cooling towers, and augmented stream flow. In the discussion of the individual components it was suggested that they might well be used in conjunction with other means described.

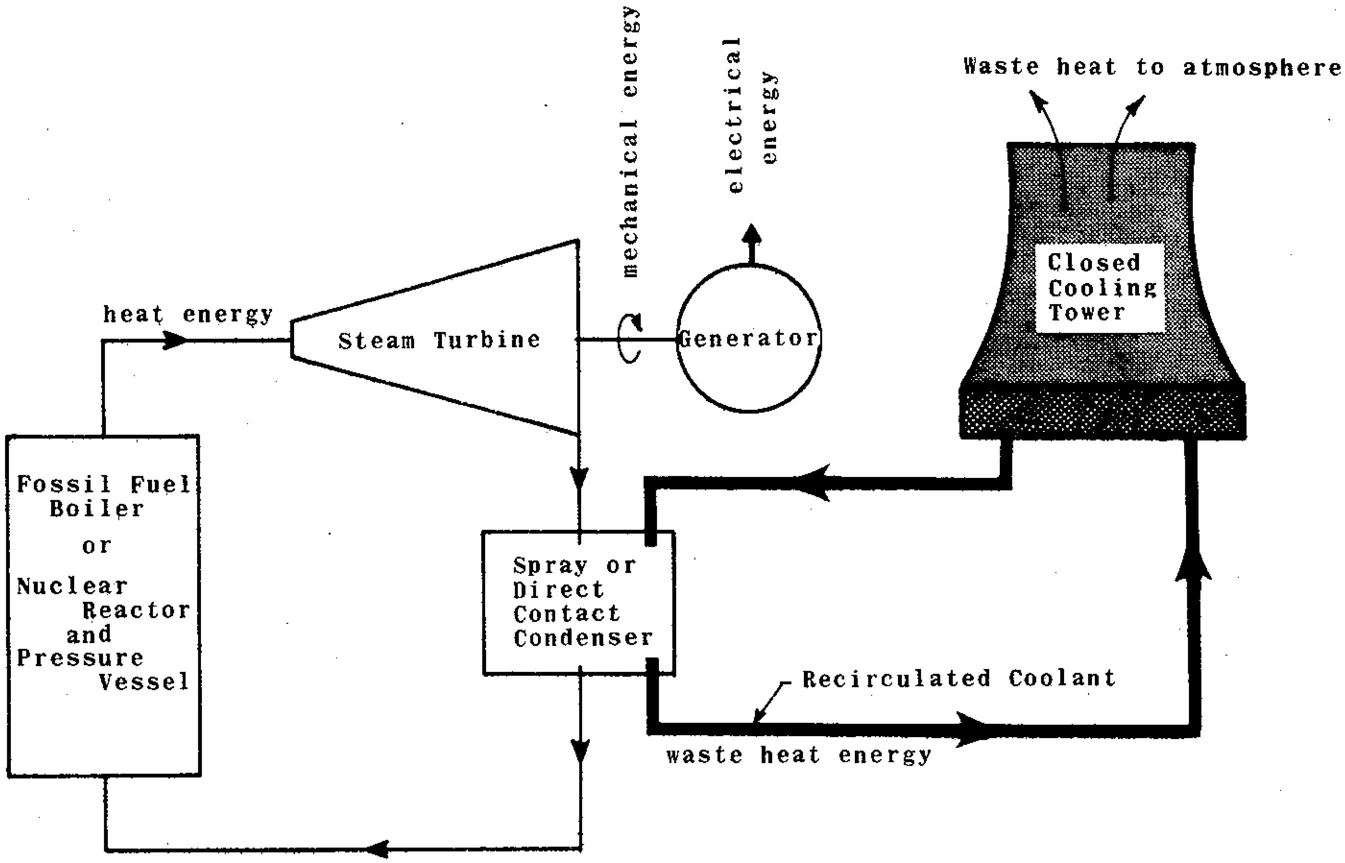
Several combinations of components have been utilized and experimented with. Most popularly employed has been the cooling tower acting as a buffer between plant and stream. This arrangement is shown schematically in Figure 1.15. Cooling ponds have been similarly used. Also, both have been used as the sole supply of cooling water with make-up coming from a stream or municipal supply. A tower supply system is shown in Figure 1.16. Such an arrangement comes into being when no other choice is available or law will not allow discharges. Finally, ponds and towers have been used together as a buffer or as a sole source of cooling water.

Lamb, in his discussion of cooling ponds describes the use

Figure 1.15 Stream & Tower Hybrid Cooling System



Power Generation System with
Hybrid Cooling System using Stream & Cooling Tower
may include Flow Augmentation for dilution cooling



Power Generation System with
Closed Cooling System

Figure 1.16 The Closed Cooling System

of mechanical cooling devices successfully incorporated into the system. An arrangement similar to the one he investigated is shown in Figure 1.17.

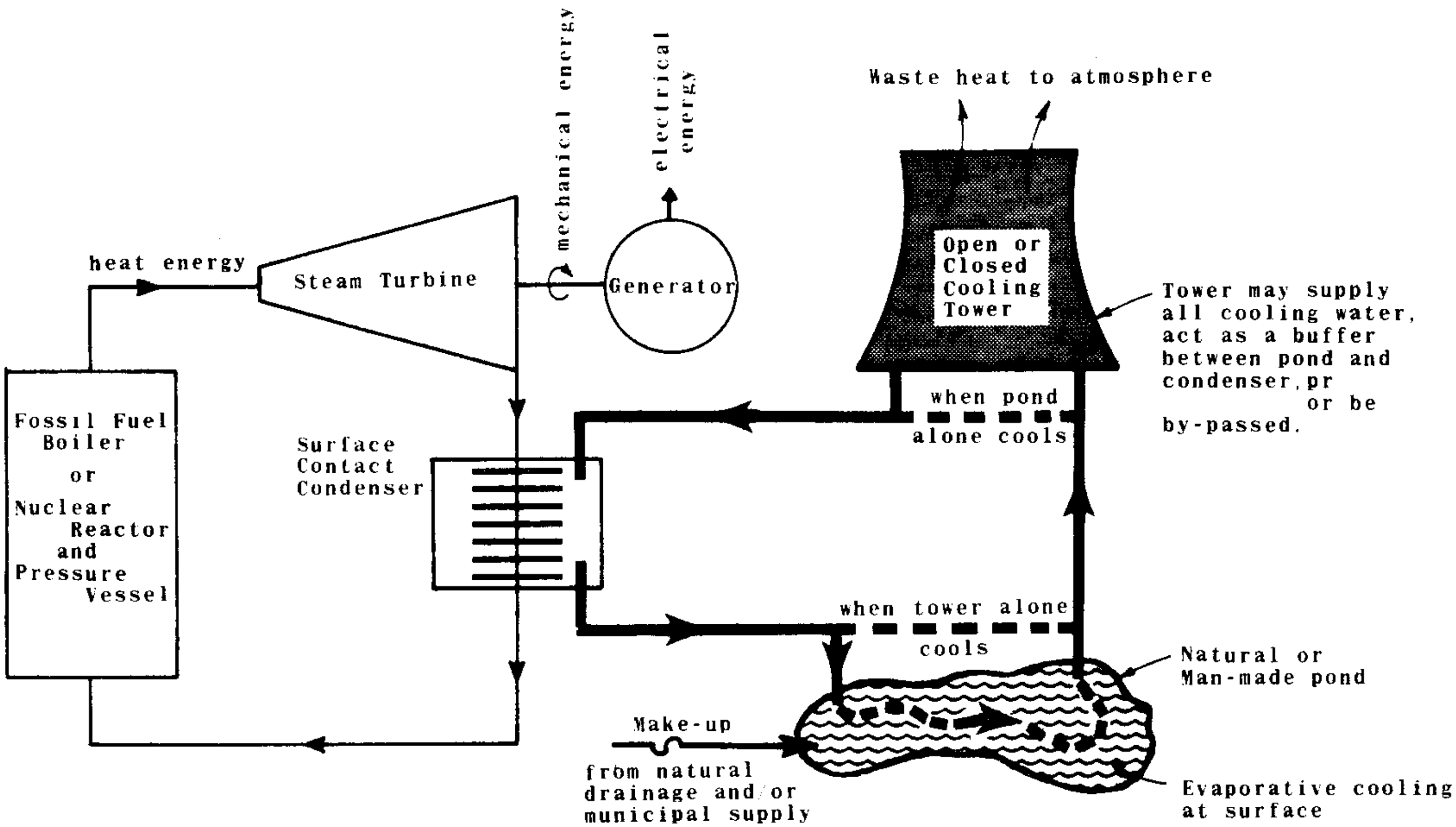
1.5 POSSIBLE CONSTRUCTIVE USES OF WASTE HEAT

Another direction exists concerning the problem of discarding vast quantities of waste heat that was not touched upon in the previous section.

Opposed to designing methods of disposing of waste heat is the possibility of finding new ways to redirect and use it. Rather than allowing those vast quantities of thermal energy to go undirected into natural environments, the goal is to create systems that will take advantage of and use this energy.

The question that remains then is, what type of system might take advantage of this waste energy which is upsetting natural environmental balances? It has been suggested most recently by J. A. Mihursky[16], that properly designed systems could take advantage of waste calories and make them biologically useful. Biological systems have been used to alter or convert waste materials and are widely accepted technique. However, these systems are relatively simple and most serve only a single purpose. A sewage treatment plant is such a system, as it establishes an environment which allows waste materials to break down into harmless wastes which then can be released to the environment. Many other examples of similar systems are available. The goal, to be emphasized, is one of creating a more elaborate

Figure 1.17 Tower & Pond Hybrid Cooling System



Power Generation System with
Hybrid Cooling System using Tower and Pond

ecosystem which might convert waste materials and energies into food stuffs, for example.

Recyling systems which facilitate the creation of closed systems capable of using its own wastes have been of foremost concern among ecologists. Imaginative thinking among pollution ecologists has suggested closed system designs which take advantage of organic wastes to provide necessary nutrients while waste heat from steam electric installations provide optimal temperature ranges for maximum biological activity and production.

H. T. Odum [17] describes the task in very simple but effective terms. "Components must be selected from the world's stock shelves, and combined into new circuits within the master circuit of the environment". Much work remains to determine what life forms can work efficiently together in forming these new ecosystems or food chains which will biologically convert available waste energy into valuable materials or food stuffs. One area which must be given immediate attention by ecologists is that of understanding energy flow in relation to population diversity and structure within man-made ecosystems. The question raised most often asks: "does a simple or complex population produce the most efficient ecosystem in terms of energy conversion." Answers to this, among other questions may bring closer to reality the creation of such ecosystems and a possible solution to the problem of waste heat disposal.

Mechanical systems might also serve as one means of returning to heat balance in nature once again. Several direct uses of waste heat have been adopted and have been of moderate success. One instance has been the use of waste heat from steam electric stations to heat large apartment blocks. Understandable limitations have been recognized regarding the transmission of the heated water, the cost of piping being most often the governing factor. The system has been used in England where it was shown that it can only be applied economically when there is a sufficiently high population density. Of course, it must be recognized that the needs of the potential heat users are seasonally out of phase with those of the heat disposer. Therefore, the economic justification of a distribution system would have to be based solely upon revenues from the sale of heat which could otherwise be disposed of at virtually no cost. This use of waste heat, then, may or may not have application with regard to the original problem.

Another application that has not as yet been pursued is the direct use of steam from a nuclear power plant to desalinate water. Such arrangements have been employed except that the steam to be used in the desalination process was accounted for in the original design of the steam generators. Conceivably, the system could be designed so that only the heat which would otherwise be wasted would be used in the sea-water conversion operation.

1.6 PREVIOUS RESEARCH EFFORTS CONCERNED WITH THE ENGINEERING ASPECTS OF THE WASTE HEAT PROBLEM

In order to view in proper perspective the events which have lead to the present state of knowledge, studies concerned with heat dissipation from streams will be reviewed in chronological order. Each of these works has contributed to the solution of various aspects of the total problem and none can be ignored if a truly comprehensive study is being undertaken. This review will only outline the content of each study, indicating the particular areas which ultimately contribute to a fuller understanding of temperature distribution and dispersion within stream environments. A review of these contributions is prerequisite to the undertaking of a thermal study.

The earliest notable contribution was made in 1946 by M. LeBosquet, Jr.[18] His studies of water temperatures and their effect on water requirements for dilution of residual organic pollutants following various treatment processes led to the development of a temperature formula. This formula enabled the determination of necessary flows as a function of temperature and other water quality criteria. His derivation also results in an equation, which after having evaluated certain parameters, enables computations of expected temperatures under new conditions.

Final conclusions concern the several benefits of increased stream flow to cooling water use. An obvious benefit is that the same amount of heat raises the temperature of a larger volume of water to a lesser degree. This assumes of course that mixing takes place with the additional flow. A second benefit is that the amount of recirculated water is reduced. Increases in flow may benefit conditions in the immediate area while downstream users may not benefit. Under circumstances of increased flow it may be found that the heat load may not have time to dissipate to the atmosphere before it reaches other downstream points. This results from a reduction in the time-of-travel upon increasing flows.

The financial benefit of reducing stream temperatures by increased flows, in itself, will not be sufficient to justify the cost of an impoundment. It will, however, be justified if it is considered another function of a multiple purpose project.

The U. S. Geological Survey's work at Lake Hefner(19) on water loss investigations represents the most thorough study of evaporation from reservoirs to date. Their results are believed to be likewise applicable to flowing stream water surfaces with only slight modification. The USGS studies centered around the investigation of four basic methods for determining evaporation. These included the energy budget, mass transfer, water budget, and evaporation pan methods. Their work on the energy budget method yielded theoretical foundations which formed a starting point for the works which followed. The various mechanisms operating to alter the energy content were analyzed in detail - in such detail that it is difficult to extend or improve their theoretical work. Included in this theoretical work are discussions of solar radiation, reflection of shortwave radiation, effective back radiation, radiation from clear & cloudy skies, advected energy, conductive and evaporative energy. The Geological Survey's work is discussed further in sections to follow.

Harbeck and others[20] described their studies at Lake Colorado City, Texas, in which they devised means for predicting the increased evaporation and temperature, which resulted from the addition of heat from a power plant. This work followed closely the directions established by the Lake Hefner studies utilizing the various budget methods of analysis.

Gameson, Hall and Preddy[21] studied the effects of heated discharges on the temperature of the Thames Estuary. Their basic premise, and one which is emphasized by this writer, is that a knowledge of the rate of exchange of heat between the water and the air is required before the effects produced by a new power plant installation or by changes in the discharge of heat from existing stations can be calculated. Their work included statistical studies of daily air and water temperatures, the measurement of estuary water temperatures, estimation of temperatures under natural conditions, a survey of heat entry rates into the estuary, calculation of excess heat dissipation rates, and forecasting temperature patterns for unit inputs of heat at various points in the estuary. They utilize the idea of a proprotionality constant suggested by LeBosquet when equating the total rate of heat entry to the total rate of loss of excess heat.

Another valuable contribution was that made by Velz and Gannon.[22] Their application of statistical methods to the analysis of meteorologic and hydrologic parameters represents an example of which should be followed. Attempts to forecast the heat loss from streams necessitates a probability analysis of events which influence water temperature. Upon developing the basic heat budget relationships they apply all the foregoing when determining pond and river water temperatures. Their conclusions underlie one of the hypothesises of this presentation. Basically, they reason that with a rational method of forecasting expected water temperature patterns, it is possible to evaluate the potential temperature effect of proposed facilities utilizing stream water. They also indicate that this will aid in site selection for steam electric power plants.

Raphael,[23] in a paper entitled "Prediction of Temperature in Rivers and Reservoirs" discussed for the most part the various components of the well known energy budget relationship. He includes more detail in several areas than was presented in previous work. Also described is a numerical procedure for determining temperature changes over finite intervals. This last section is only a brief presentation which is supplimented in sections of this paper to follow.

A committee report from Johns Hopkins University entitled "Heat Dissipation in Flowing Streams"[24] provides a comprehensive review of the environmental heat exchange mechanisms. Also valuable discussions of in-stream temperature equalization by turbulent diffusion and exponential decay of stream temperature are included. The remainder of the presentation is concerned with a river study which confirms or denies the impressions gained from review of the theory. A procedure for data analysis is presented along with a section concerned with the application of analytical methods. Finally, two areas not discussed by earlier investigators, namely field surveys and instrumentation are covered briefly.

Duttweiler,[25] one of the committee members of the previously reviewed work, then proceeded to investigate the exponential decay of excess stream temperatures and developed a mathematical model based on this concept. Duttweiler introduces a new concept of a temperature input function which is given as a function of observable climatological variables. The model is given a limited test which showed it to be useful in estimating temperatures below heated discharges and below the release of stored water in low-flow augmentation.

A conclusion which has appeared in many other writings emphasizes the difficulty of data collection and consequently the shortage of such data. This is a serious handicap to successful temperature prediction.

Edinger and Geyer[26] in their cooling water studies for the Edison Electric Institute entitled "Heat Exchange in the Environment." present a collection of information and ideas which was the most comprehensive in its day. They develop a heat exchange equation which is rearranged to produce a temperature equation. A study of a power plant discharge necessitated the discussion of data reduction techniques ultimately aiding in the analysis of heat distributions. Their findings are applied most interestingly to rivers and streams.

Pritchard and Carter[27] investigate the problem of predicting the probable distribution of excess temperature from a heated discharge in an estuary. A specific case is investigated but the authors contend that the techniques described have general application. In that, temperature distributions within an estuary, where greater mixing due to tidal action, are sought, a major portion of the writing is concerned with dispersion both in field studies and theory. Their work on the dispersion of heated effluents is certainly the most complete to date.

CHAPTER II

THEORETICAL BACKGROUND

2.1 THE NATURAL THERMAL LOAD

All natural heat in streams comes directly or indirectly from the radiant energy of the sun. The effect of solar radiation is illustrated by the fact that the temperature of rivers will rise several degrees from morning to afternoon depending on the amount of cloud cover.

The incoming solar radiation is short-wave radiation varying from .14 to 4.0 microns, (peak intensity at .5 microns) which passes directly from the sun to the earth's surface. The amount of solar radiation striking a given body of water depends upon the altitude of the sun, geographical location (latitude on the earth), time of day, the season of the year, cloud cover, shading, and quantity of indirect solar radiation. The amount of short wave radiation reaching the water body also depends upon the amount of water vapor and particulate matter in the atmosphere. Experience has shown that it is more easily measured than computed. A pyrheliometer, which is an instrument that responds only to short wave radiation, is used for its measurement.

Atmospheric radiation is longwave radiation, varying from 4.0 to 120 microns, (peak intensity at 10 microns) which passes from gases in the atmosphere. This type of radiation does not follow a simple law. It is a function of many variable, notably the distribution of moisture, temperature, ozone, and carbon dioxide. Longwave radiation may be estimated by use of empirical formulae which accounts for some of the above variables. Of the several formulas, Brunt's is one receiving most attention. The formula for determining radiation from a clear sky appeared as follows:

$$Q_a = T_a^4 \sigma (a+b(e_a)^{1/2}) \tag{2.1}$$

where, Q_a = The atmospheric radiation from a clear sky

σ = Stefan-Boltzmann constant

T_a = Absolute temperature of the air

a, b= empirical constants

e_a = the vapor pressure of air near the ground.

This formula attempts to relate atmospheric radiation to the local vapor pressure while it should be related to the total vapor content of the atmosphere, the content of various gases and possibly other unknown factors. It must be understood then that this empirical relation gives only average evaluations of atmospheric radiation. Various series of measurements fitted to Brunt's formula gave "a" values from 0. 34 to 0. 62 and gave "b" values from 0. 029 to 0. 082. This is an indication of the approximateness of the formulation.

If there is cloud cover, atmospheric radiation is greatly increased. Investigations (19) have yielded results in the following form:

$$Q_{ac} = T_a^4 \sigma (1 - \lambda) + Q_a \lambda \qquad 2.2$$

where, Q_{ac} = atmospheric radiation from an overcast sky

T_a = absolute temperature of the air

σ = Stefan- Boltzmann constant

λ = empirical coefficient which is a function of cloud height

Q_a = the atmospheric radiation from a clear sky.

Experience has shown that for short intervals, and for times when clouds are present, it is necessary to measure atmospheric radiation directly. However, it has also proved possible to evaluate from empirical relations the atmospheric radiation received from a clear sky over a long period of time.

Reflected solar and atmospheric radiation must also be evaluated when attempting to find the net energy input to the water body. Solar reflectivity, the ratio of reflected radiation to incident radiation is more variable than the atmospheric reflectivity. The first is a function of the sun's altitude and the type and amount of cloud cover, while the last is relatively constant. These reflectivity values are used to determine the net incoming solar and atmospheric radiation. On striking a water surface, a portion of the light is reflected-as much as 35percent, depending upon the angle of incidence.(2)
Light penetrating the water is absorbed at different depths depending on the amount of suspended and dissolved substances in the water and the wavelength of the light. The longer wave lengths (infrared, red

and orange), and the shorter wavelengths (ultra-violet, blue and violet) are absorbed more quickly than the middle range wave lengths of green and yellow. In the first 3 feet of depth as much as 50 percent of the total incident light may be absorbed where it is transformed into heat.[28]

Heat is also received indirectly by the solar heating of watersheds, which in turn warm the rain that falls on them. The addition of heat from this source is only minor but it should be recognized before being neglected. With watersheds being altered to much greater extents, run-off temperatures are influenced more by land temperatures. This is true for irrigated lands where water in ditches is heated by the sun. Run-off from paved areas such as highways and parking lots is becoming a larger proportion of the total run-off, of course at this point it is still negligable. On the other hand the specific heat of earth and rock is only one fifth that of water indicating that water flowing over the ground cannot pick up that much heat. Also there would be a larger wetted surface area exposed to the air resulting in a higher rate of evaporation and in increase in the rate of heat dissipation. Of course, these rates depend upon the air-water temperature difference and the dew point of the air, both of which vary from point to point. These considerations point out the complexity of determining the net increase in the natural thermal load of streams. In the final analysis these contributions must be ignored.

2.2 THE ARTIFICIAL THERMAL LOAD

The artificial thermal load is directly attributable to many municipal and industrial processes. Although steam power plants and certain industries are major contributors to thermal pollution, all industrial activity contributes to some degree. Steam generation and cooling are unique water uses in that they are required in almost every industry. The total water intake of both industrial manufacturing plants and investor-owned thermal electric utilities was approximately 48,900 billion gallons during 1964.*[29] About 90.4 percent of 44,234 billion gallons per year (bgy) of all intake water was used for cooling or condensing purposes. It is estimated that 57,285 bgy will be used in 1970. This figure may be substantially larger in light of the fact that 1964 eatimates were placed at 40,670 bgy as to the 44,234 bgy measured. It is estimated that recirculation in these plants is 5,815 bgy, so that one-through cooling required 34,849 bgy. These figures do not include water used in public owned steam generation plants for which no data were available.

The total water quantities used for single-pass cooling for 1964 are summarized in the following table.

Use		Water Quantities, bgy
Industrial- Steam Electric Generation	=	2,856
- Other	=	6,529
Commercial Power	=	34,849
		44,234

*(The data on this and the two following pages are from reference 29)

A further breakdown of these water quantities can be made by identifying the water as fresh or brackish.

	Water Quantities, bgy		
	Industrial	Comm. Power	Total
Fresh	6,549	23,104	29,653
Brackish	2,836	11,745	14,581
Totals	9,385	34,849	44,234

Water used for processing, including water coming into contact with the product as steam or as coolant, amounted to only 7.6 percent (3,700 bgy) of the total water intake. The remaining 2.0 percent (959 bgy) was used for boiler-feed water.

Brackish water, water containing more than 1000 mg/l dissolved solids, amounted to nearly 30 percent(14,600 bgy) of the total intake (34,300 bgy) was surface water delivered by company-owned water systems. Nearly all of the fresh water intake used for cooling or condensing purposes (29,653 bgy) is discharged to streams and rivers.

It is pertinent to note the rapid rate of increase in the generation of thermal-electric power in the United States during the period from 1945 to 1965. (Figure 2.1) Most worthy of our attention is a consideration of the predicted trends in thermal-electric power development. As presented for the period 1965-1985 by Ritchings, a startling need and growth is foreseen. During this twenty year

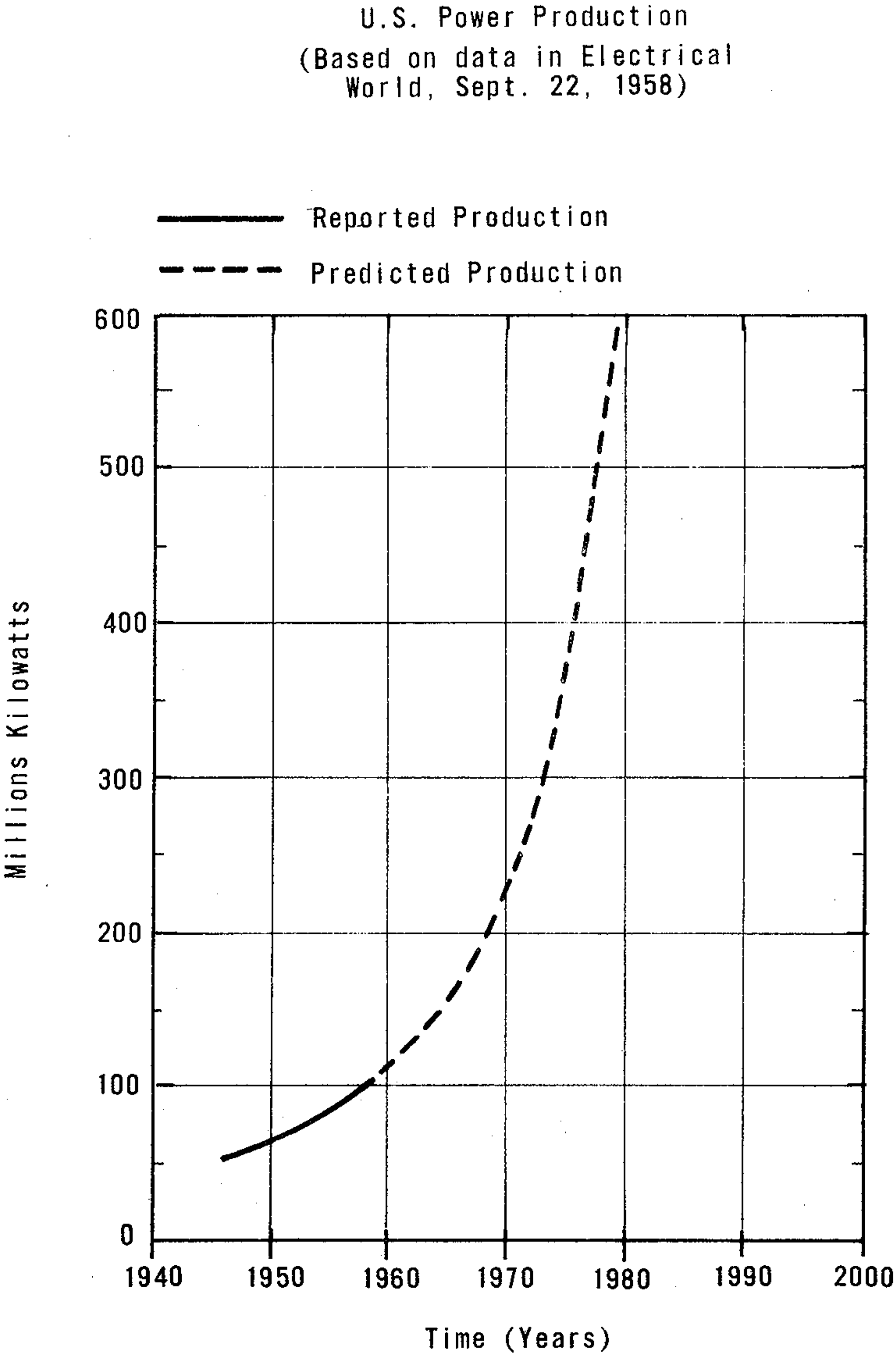


Figure 2.1 U.S. Power Production

period, a time span, which is less than half of the average man's working years, the U. S. electric utility generating capacity will increase 260 percent, from about 235, 000 to about 850, 000 MW.

The electric utility energy generated will increase 250 percent, from about 1050 to 3700 billion KWH/year.

Electric utility energy requirements per capita will increase 150 percent, from about 5500 to about 13, 500 KWH/year. At the same time, our population will increase by less than 35 percent, from 195 million to 265 million people.

Specific data has been gathered which establishes the predicted needs of the Connecticut River Basin.[30] It is estimated that in the period 1965 to 2000 the power needs of the basin will increase 330 percent from 1, 740 MW to 7, 500 MW (Figure 2. 2). This growth will be necessitated by a population growth of about 90 percent from 1. 6 to 3 million in association with an increase in per capita usage of 93 percent from 1. 5 to 2. 9 KW (Figure 2. 3). Another significant factor, concerning the use of cooling water by thermal-electric plants, is the trend toward larger individual power generating stations. Many factors are responsible for this trend. Efficiency of operation, of course is the prime reason. Also, the addition of generating plants on a utility company pool instead of on an individual company basis will accelerate the trend to larger units. The utility industry will install the largest units that the manufacturing industry can provide.

Present and Estimated
Power Needs for
the Year 2000
in the Connecticut River Basin
(From : EBASCO Report, 1966)

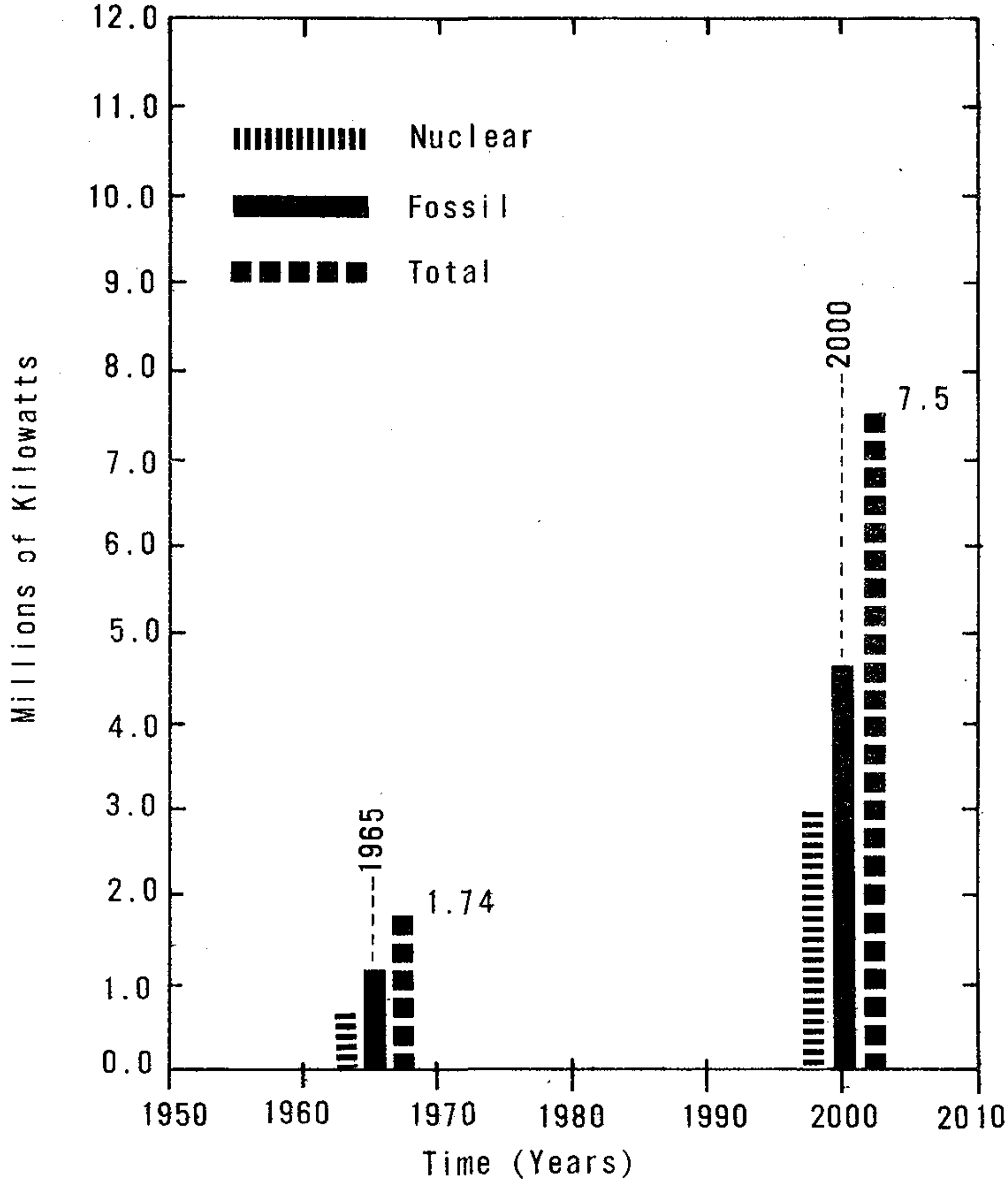


Figure 2.2 Connecticut River Basin Power Needs

Population and Per Capita Increase of Power Usage in the Connecticut River Basin

(From : EBASCO Report 1966)

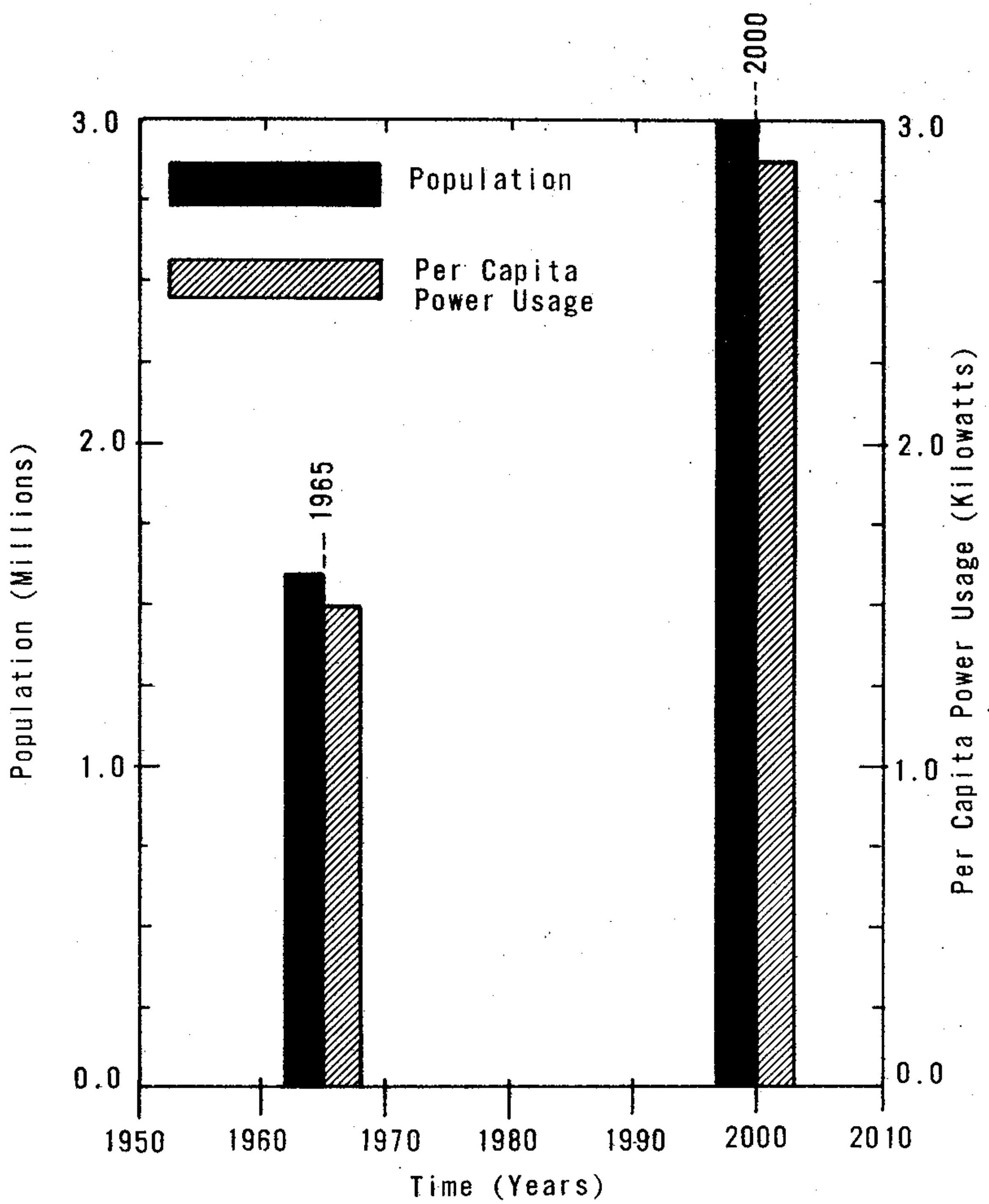


Figure 2.3 Population & Per Capita Power Usage Increases in the Connecticut River Basin

Manufacturers indicate that units will increase steadily in size to about 3000 MW in 1984. (Figure 2.4) Such high capacity plants require large quantities of water for condenser cooling. It has been found reasonable to estimate the increase in thermal energy to the condenser cooling water as approximately 4,000 BTU for each KWH of power generated. On this basis, a 500 MW plant operating at full load will reject about two billion BTU per hour.

Another point of concern necessary to understanding the trends in the utility industry is availability of energy sources. In the past, competing fossil fuels were almost equally available, the choice being simply one of economics based on fuel price, efficiency and investment requirements. This has also been true of the choice between fossil and nuclear energy sources. Today, a new criterion requires consideration. This is the availability of fuels. So in the final annalysis, price is secondary to availability. Taking into account all factors of availability, probable price levels, and uses for purposes other than power generation, it is estimated that energy sources for power generation will be as shown in Figure 2.5. Note that by 1985, the electric energy generated by nuclear sources will be more than 50 percent greater than the total electric energy generated by all sources in 1965. This increase is attributable mainly to increased efficiency both economic as well as mechanical.and thermal.

It has been the understanding of the significance of values of this

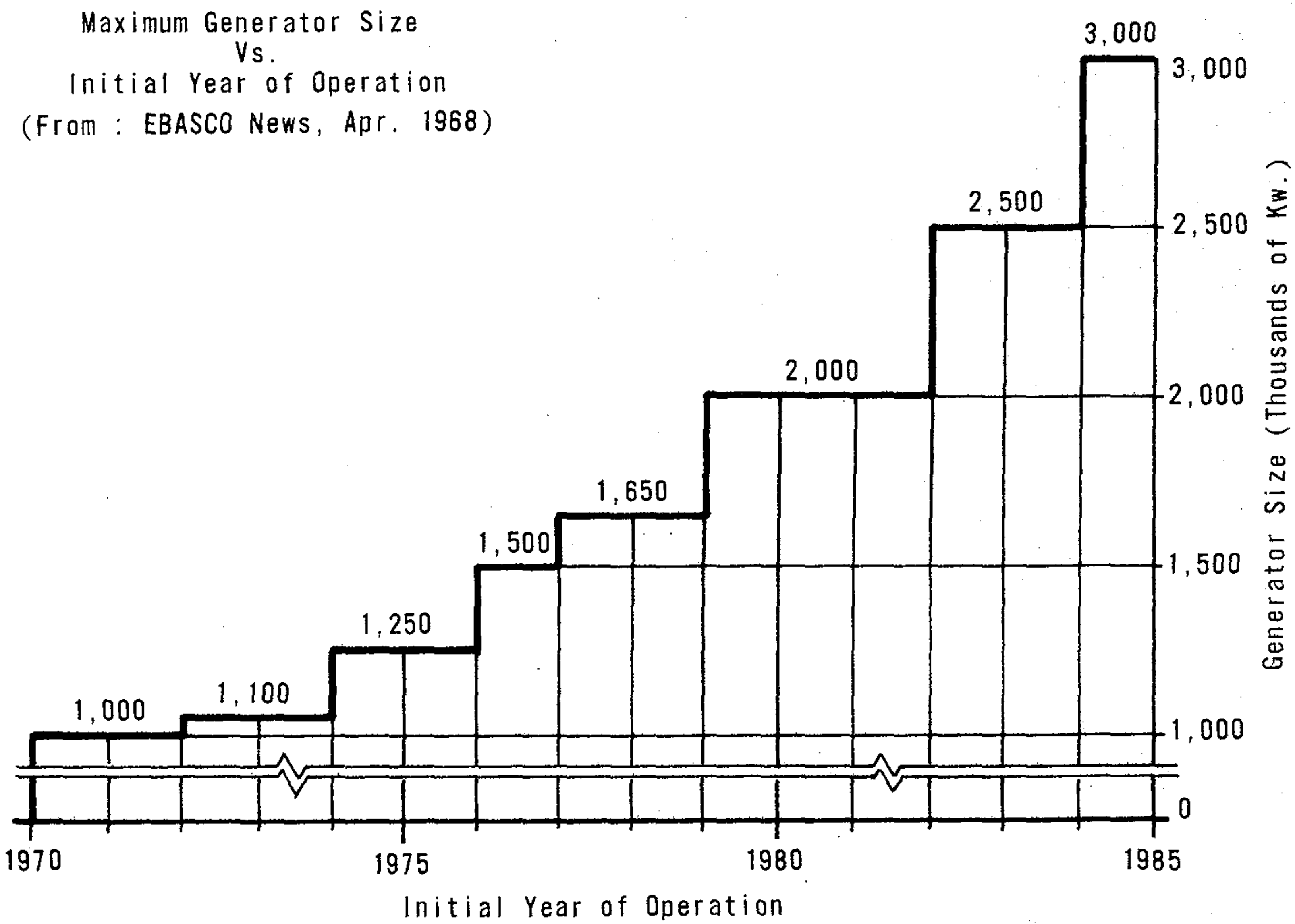


Figure 2.4 Generator Size Growth

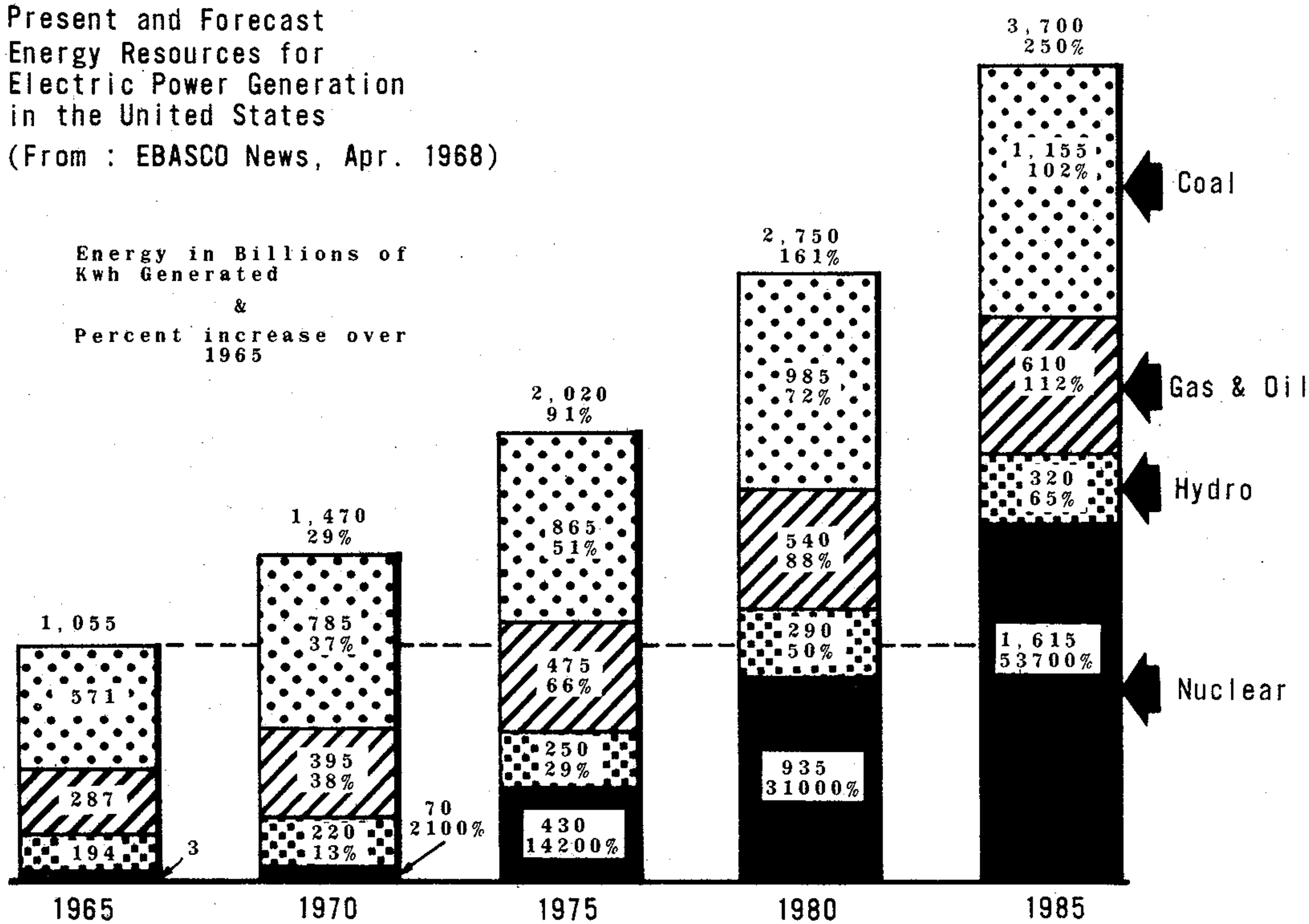


Figure 2.5 Energy Resources for Electric Power Generation

magnitude that has caused recognition of future cooling water requirements and the need to safeguard against possible damaging thermal pollution.

The quantities of cooling waters needed by a thermal-electric generating plant depends not only upon capacity but also upon the intake temperature of the cooling water supply and the design of the condensers in operation. A single-pass condenser may have a temperature rise in the order of 12 degrees F. while a multiple-pass condenser may have a temperature rise of about 16 degrees F. On the basis of the above temperature rises, a 500 MW power generating plant equipped with a single-pass condenser would require approximately 338,000 gpm or 750 cfs of cooling water. The same plant provided with multiple-pass condensers would require approximately 250,000 gpm or 563 cfs of cooling water. These figures are estimated for a plant using fossil fuel. Based on the present state of technology (1968) of the nuclear development of electrical power it is found that the amount of heat rejected to cooling water is about 15 percent greater than for fossil fuel plants.

The quantities of water required for a once-through cooling system are huge and must be drawn from amply large sources, such as rivers, lakes, or reservoirs. They are returned to those sources or other large bodies of water after having passed through heat exchange equipment just once. In recirculating cooling water systems, the water withdrawn from the river or lake is small in comparison with the rate of circulation through the heat transfer equipment.

2.3 DISSIPATION OF THE THERMAL LOAD

Evaporative cooling is an important factor in the dissipation of heat from surface waters. Each pound of water that leaves as water vapor carries its latent heat of evaporation of 970 BTU. Thus, the evaporation of one pound of water will have the theoretical effect of lowering the temperature of 970 pounds of water 1 degree F. or proportionally more for a smaller volume. Evaporation is a function of the water content of the air adjacent to the water surface. When that layer of air is saturated with water vapor the net evaporation is zero because the number of water molecules leaving the water surface is exactly balanced by the number condensing on the surface.

Wind velocity has an important effect on evaporative cooling because it can sweep away and replace saturated air with air containing less vapor. Wind speeds have been measured successfully using either a cup or a propellar type anomometer. The reference height which has been used in past heat budget studies has been twenty-four feet above the water surface. For lakes and large reservoirs this seems satisfactory in that local terrain has little influence on wind conditions. It appears reasonable to expect that lower reference heights and more installations will be required along streams and rivers where high banks, valley walls, adjacent structures, trees and other growth will influence local wind conditions.

There are many methods for estimating evaporation. The four generally accepted methods for computing evaporation are: (1) water budget; (2) energy budget; (3) mass transfer; and (4) water surface to pan relations. These methods were originally investigated as an aid in reservoir design but can be applied to heat loss studies, as here considered. Very few reliable water budget estimates are available because small errors in volume of inflow and outflow usually result in large errors in the residual evaporation value. The energy budget approach requires such elaborate instrumentation that it is only feasible for special investigations. The mass transfer method requires observations of surface-water temperature, dew point, and wind movement which are available for only a very few reservoirs. From a practical point of view, evaporation can most easily be estimated using pan evaporation and related meteorological data. There is, however, no method of measuring evaporation directly, the closest attempt to a direct measure being the water study. The Lake Hefner Studies, of the U. S. Geological Survey, were set up explicitly to develop an empirical formulation of evaporation related to meteorological variable and utilized the water budget approach as a "direct" measure of evaporation. An evaporation formula was developed which gives the rate of evaporation as proportional to the product of wind speed and the difference between the value of the saturated water vapor pressure at the water surface and the water vapor pressure in the air. The general form of such an equation is:

$$Q_e = (a + bW)(e_s - e_a) \qquad 2.3$$

where,

Q_e = heat lost by evaporation, BTU/(sq. ft.)(day)

a, b = coefficients depending on the formula employed

W = wind speed in miles per hour

e_a = air vapor pressure in mm - Hg

e_s = the saturation vapor pressure of water determined from the water surface temperature.

These coefficients have been evaluated for different lakes under study. It is expected that the coefficients would be much different for rivers and streams than for lakes and might well be dependent on water velocity and turbulence, particularly in the case of small rivers. Velz and Gannon(22) suggest a very similar form of the basic equation.

$$Q_e = C(a + bW)(e_s - e_a) \qquad 2.3.1$$

For flowing streams of moderate depth and velocity, C may be taken as 14, a = 1, and b = 0.1. When converted to units consistent with previous developments we have:

$$Q_e = 0.00722 \ \lambda \ C(1 + 0.1W)(e_s - e_a) \ \text{BTU/(hr.)/(sq. ft.)} \qquad 2.3.2$$

The heat lost by evaporation can also be expressed as a function of the volume of water evaporated, its density and the latent heat of vaporization of the water at the temperature of the water surface. This relationship is represented as follows:

$$Q_e = V_e \ \lambda \ \rho_e \qquad 2.3.3$$

where,

Q_e = heat lost by evaporation, BTU/ft^2/day
V_e = Volume of water evaporated, ft^3/ft^2/day

λ = latent heat of vaporization of evaporated water BTU/lb

ρ_e = density of evaporated water lbs/ft^3

It can be seen then that the heat loss by evaporation can be determined once the volume of water is known. This returns us to the original problem of determining accurately the evaporated volume.

Heat may also be dissipated from the water body by conduction. This, of course, assumes that the water is warmer than the adjacent air mass. The transfer of heat theoretically takes place according to the following law:

$$Q_c = - Cp\, A\, (dT/dz + \gamma) \qquad 2.4$$

where,

Q_c = conductive heat loss, BTU/ft^2/hr.

Cp = Specific heat of air at constant pressure, BTU/ (lb) (degree F)

A = vertical component of eddy conductivity

dT/dz = Temperature gradient of the air, degree F/ft

γ = Adiabatic lapse rate.

Efforts were made in the Lake Hefner Study (Anderson, 1954) to evaluate eddy conductivity. It was found that certain of the variables could not be measured with enough precision so the use of the above equation was hindered. To overcome this problem, the technique for estimating conductive heat loss devised by Q. S. Bowen, 1926, [31] was employed. It is possible to obtain a knowledge of the gross magnitude of the conducted heat through use of the Bowen ratio. The ratio, R, of conducted heat to energy utilized by evaporation was theoretically related to easily measured quantities. R was defined as follows:

$$R = \frac{c\, P_{atm}\, (T_s - T_a)}{1000\, (e_s - e_a)} \qquad 2.5$$

where,

R = Bowen Ratio

c = a coefficient which ranges from 0.58 to 0.66 depending on atmospheric conditions and surface roughness. 0.61 is used for normal atmospheric conditions.

T_s = water surface temperature, degrees F

T_a = air temperature, degrees F

e_s = saturation vapor pressure at the water surface temperature, millibars*

e_a = vapor pressure of the air, millibars

P_{atm} = atmospheric pressure, millibars.

The variability of the Bowen Ratio with time, together with the necessity for making a quantitive estimate of evaporation in order to fully evaluate heat transfer, established doubt concerning the utility of the heat budget approach to predict short-term stream temperature changes.

*A millibar is a unit of pressure equal to a force of 1.45×10^{-3} p.s.i. or 2.05×10^{-5} in. Hg.

The expression for the rate of heat conduction can be written using the general form of the evaporation formula discussed previously.

$$Q_c = \frac{c\, P_{atm}\, (T_s - T_a)\ (a + bW)}{1000} \qquad 2.6$$

Q_c = heat lost by conduction

c, P_{atm}, T_s, T_a, a, b, and W have been defined previously.

Observing this equation it can be seen that when the air temperature is greater than the water temperature, the sign is negative and the thermal gradient favors the conduction of heat from the air to the water. Heat is conducted from the water to the air when the gradient is in the opposite direction.

Heat energy is also dissipated from the water body by convection. This is heat carried away by the evaporated water when its mass is transferred at constant temperature from the liquid to the vapor state. All of the heat is transferred by the actual evaporation process and is considered to be part of the latent heat of vaporization, but since the molecules which are evaporated had some temperature before the evaporation process began, and since evaporation takes place at a constant temperature, the process causes the molecules of water evaporated to carry sensible heat with them. This amount of heat is a function of the amount of water evaporated, its specific heat, and its ambient temperature, measured above an arbitrary base temperature. Convective heat loss may be represented as follows:

$$Q_w = \rho_e V_e C_p (T_e - T_b) \qquad 2.7$$

where,

Q_w = convective heat loss, BTU/(sq. ft.) (hr)

ρ_e = density of evaporated water lbs/(cu. ft.)

V_e = volume of evaporated water (cu. ft)/(sq ft)(hr)

C_p = specific heat of water, BTU/(lb)/(degrees F)

T_e = temperature at which evaporation takes place degrees F

T_b = arbitrary base temperature, degrees F

It is readily seen that the accuracy with which convective heat loss may be determined is directly influenced by the accuracy with which evaporation may be estimated.

Heat energy may also be advected into or out of a body of water. It is necessary to study the climatological, hydrological, and geographical characteristics of the particular location. These characteristics influence the choice of the most suitable method for measuring advected energy. It is not possible to establish a method that will apply in all cased, but it is possible to derive certain general principals.

Advected energy is defined as the energy lost or gained by a body of water through the inflow or outflow of a volume of water. Advected volumes may result from surface inflow, rainfall, seepage, bank storage; and controlled outflows. In some situations all these must be considered, while in other situations some may be neglected.

2.4 GUIDELINES FOR THE SOLUTION OF THERMAL PROBLEMS

More and more it will become routine to find included in the design of industrial cooling systems an analysis of the effect of waste heat discharges on the surrounding environment. Such analyses are being included not usually for completeness of design but as a result of public pressure and demands. Well grounded fears, born out of ever increasing public awareness of the possible destruction of natural waterways and recreation areas by excessive amounts of waste heat have placed a burden upon systems, designs and analysts.

In view of the vast number of analyses which will be necessarily carried out in the years to come as well as for the other reasons previously cited, a framework of guidelines and criteria will be established to aid in the solution of thermal problems. These guidelines will not only point a direction to newcomers but also establish a uniformity among solutions - a further aid to subsequent studies.

2.4.1 FRAMEWORK OF GUIDELINES TO AID THE SOLUTION OF THERMAL PROBLEMS

A. Define the Problem.

1. Does a problem exist, if so, outline its nature and extent.
2. Potential growth.

B. Plan the goals of an engineering investigation.

1. Preliminary investigation or
2. A thorough engineering analysis.

C. Determine variables which must be measured and which enter into computations.

1. To supplement existing data or

2. To supply all needed data

D. Investigate data availability, data sources.

1. Data reorganization.

E. Determine the type or types of field studies necessary to supply needed information.

F. Organize and begin execution of field surveys.

1. Decisions regarding type of monitoring system, central data recording system or individual recorders, monitor locations, and the like must be made.

2. Economic considerations enter in.

G. Instrumentation and data recording.

H. Data reduction and storage.

I. Establish theoretical relationships.

J. Investigate applications of modern computation tools and techniques. This will influence the ways in which data is recorded, analyzed and stored.

K. Execute theoretical studies.

L. Establish conclusions and recommendations.

M. Consider and investigate alternate methods of bringing about desired end.

N. Draw final conclusions.

This outline represents a realistic engineering approach to the problem. Now, techniques for successfully executing the technical phases will be suggested. Organizational aids will be offered as well as helpful short-cuts. In all, a description sufficiently complete, even for those approaching the problem for the first time, will be created. If these suggestions can be standardized it would not only facilitate the solution of new and even more complex problems to come, but would also create a unity within the engineering profession for those engaged in the solution of such problems. This is one of the basic goals of this treatise.

Among the many organizational aids which could be created is the one shown in Figure 4.4 (page 108). Such a status sheet helps maintain a perspective on the collection and reduction of data necessary to implement a thermal study.

CHAPTER III

MODELLING TECHNIQUES TO SIMULATE STREAM TEMPERATURES

3.1 TEMPERATURE COMPARISONS

Comparison of water temperatures before and after man-produced changes are subject to question unless the variables can be held constant or can be accounted for in the calculations. Previous sections have shown that the variables can be accounted for, at least approximately. In a stream, as in any water body, there will be a natural pattern of temperature variations which must be known before artificial causes of temperature can be evaluated. Qualitatively, the natural variation in temperature of a stream can be shown as in Figure 3.1. This three-dimensional envelope describes the range in which temperatures could be expected to modulate. A knowledge of the shape of the envelope is indirectly one of the first goals of a thermal study. The basic premise upon which the following mathematical model is constructed is that once the mechanisms of heat transfer are combined and adjusted to yield natural temperature patterns within acceptable limits, then artificial heat loads can be introduced and resulting temperatures "automatically" determined. This assumes that each mechanism is contributing in approximately the same proportion as it does in nature. If this were not the case, the results obtained with artificial

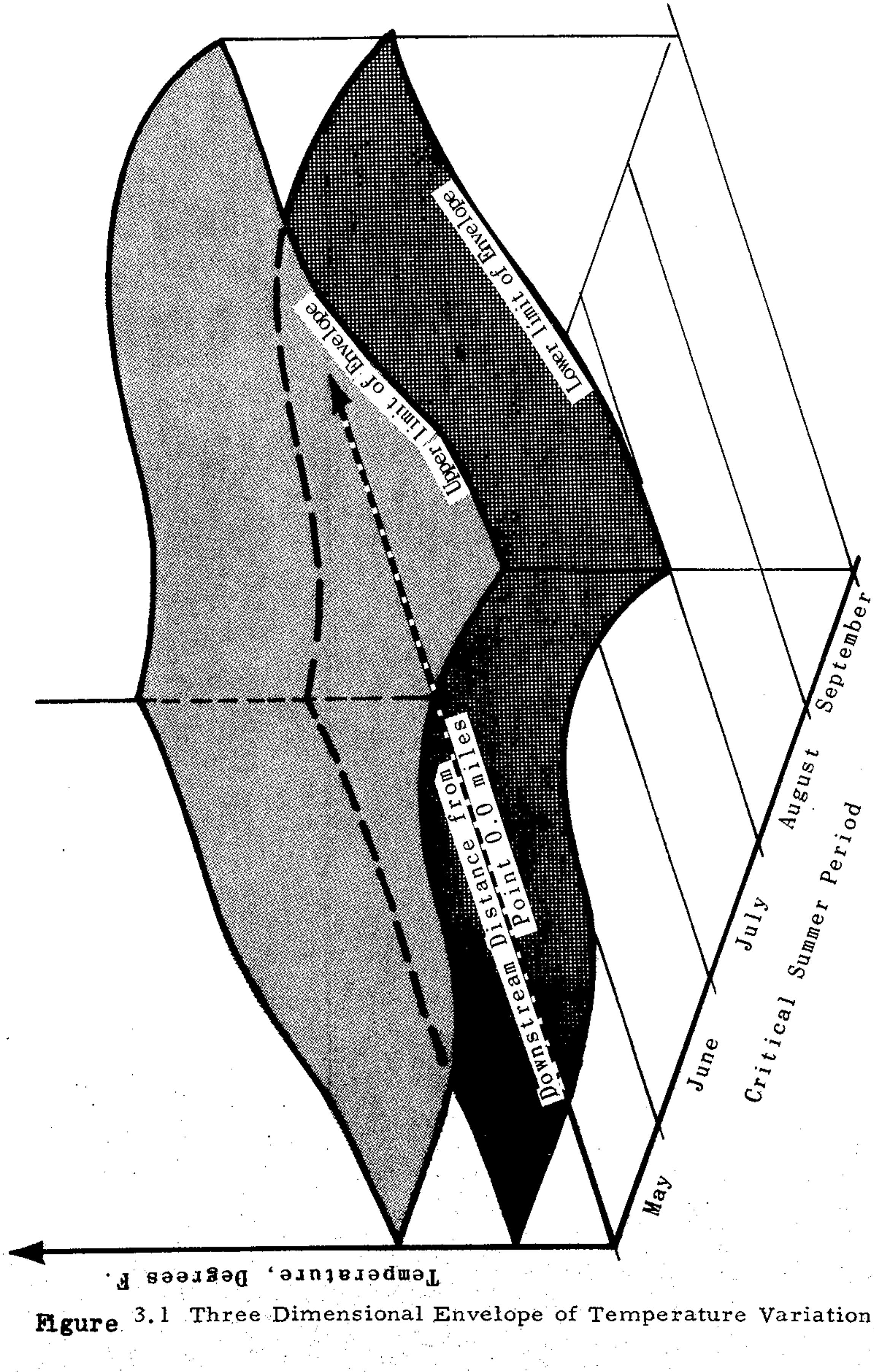


Figure 3.1 Three Dimensional Envelope of Temperature Variations heat added would be erroneous. The proposition being made here states that if all the forces acting on the system are known either through measurement or estimation, then the response of the system follows directly assuming the functional relationships are known.

An advantage of being able to predict temperature profiles subject only to natural conditions is that it facilitates the establishment of a datum from which artificial increases or decreases can be measured. This has special value where temperature data prior to the introduction of artificial thermal loads is unavailable. As was shown earlier, such data may form the basis of regulations for the control of temperature and heated discharges.

3.2 SYSTEMS ANALYSIS

Systems analysis provides a tool which organizes the decision making process for managers and engineers. Basically systems analysis is a methodical approach to a problem, with the objective of examining the problem as a whole, finding the optimum answer by considering all the aspects of the problem including any necessary constraints. This tool is actually made up of many techniques among which are mathematical modelling and linear programming. All the methods or techniques are mathematical and can be broken down into two categories, the analytic or direct approach, and the non-analytic or trial and error approach. In both approaches, the behavior of the system is expressed by a set of mathematical equations which when solved, will indicate the particular choice of action which will optimize the system.

3.3 MATHEMATICAL MODELS

Mathematical modelling is a technique which finds numerous applications in analysis of water resource problems. Ultimately the analysis seeks to determine the behavior of a real system by use of a model. Mathematical modelling is a non-analytic method which involves a trial and error solution. The system under consideration here is made up of the river basin, the atmosphere, and the sun which interact. The formulation of the mathematical model involves the use of stochastic (random) input data. Examples of stochastic input data are stream flow and atmospheric conditions. The solutions must therefore recognize the probability of events. The model of the system must permit the testing of various combinations of facilities and methods of operation in order to reach decisions about the real system.

Recognizing the complexity of the system and the resulting mathematical model, the model will be translated into language recognized by electronic computers. In order that there be alternatives from which to choose in making a decision, the input data to the program is changed thereby modifying the model. The output from the computer will describe the system's response to the particular configuration tested. Examining the responses of numerous configurations will allow choosing, hopefully, the optimum with regard to all water uses.

3.4 OPTIMIZATION TECHNIQUES

Recently, there have been developed several optimization techniques which find great application throughout all the engineering disciplines. Although these techniques will only be discussed in passing, due to time limitations, the author is convinced that these techniques will find valuable use in the ultimate solution of thermal problems.

The one technique receiving most attention by water resource analysts is linear programming. As described by IBM[32], linear programming is a mathematical technique for determining the optimum allocation of resources (such as capital, raw materials, manpower, plant or other facilities) to obtain a particular objective (such as minimum cost, or maximum profit) when there are alternative uses for the resources. The technique can also be used to analyze the economics of alternative availability of resources, alternative objectives, and so on.

It may be obvious that there are many direct applications to problems within thermal pollution studies alone. One application is that of choosing an optimum combination of temperature reduction methods to meet a predetermined limit on stream temperatures.

Others may include, determining the optimum allocation of water to its many uses, (flood control, power development, flow augmentation, etc.) optimizing the use of the stream to assimilate different types of waste (organic, inorganic or heat), or to determine the most efficient ecosystem in terms of valued fish crop, waste assimilation, and waterway aesthetics.

Linear programming does have limited application in that the equations defining the problem must be first order. Real situations do not always have a linear response - for example, the cost function of a cooling structure or a dam to supply low flow augmentation are S-shaped curves as a rule. If the range of interest, however, is limited to that portion of the curve which is approximately linear, then the technique may be employed.

3.5 THE MATHEMATICAL MODEL

The previous sections of this paper have been setting the stage for the creation of a mathematical model which will enable the prediction of effects of man-made changes in the natural environment. The task remaining is to compose the variables, their relationships, and all simplifying assumptions that have been identified into a mathematical expression. This expression will take account of all means by which energy enters and leaves the reach under study. Once the net energy flow has been determined the corresponding change in temperature is easily calculated.

The temperature environment of a stream will be studied by breaking the stream into numerous reaches and even subreaches where conditions demand. Each of the meteorologic and hydrologic variables acting to change the water temperature is assumed constant within the reach, thus facilitating the computation of the temperature change. This is basically a finite differences approach. Of course, it can be seen that if the size of each reach is reduced while their number increases, theoretically to the limits of $\frac{1}{\infty}$ and ∞ respectively, it would be possible to determine the smallest incremental change in temperature which takes place. This would yield a continuous solution. However, due to the impossible task of measuring each of the input variables in each increment, reaches of finite length are used. These reaches may be in the order of miles in length, depending primarily upon the number of points at which variables can be measured. Sections where measurements are taken, most conveniently, serve as boundaries and the average of the measurements from the upper and lower boundaries is used in determining ΔT over the reach.

Q_H is the net heat input to a reach in, BTU/sq. ft./hr. given as:

$$Q_H = (Q_{NR} + Q_{HD}/A) - (Q_{BR} + Q_E + Q_C) \qquad 3.1$$

where,

Q_{NR} = the net heat energy from the sun, taking into account atmospheric condition, reflectivity, and shading in B.T.U./sq.ft./hr.

Q_{HD} = the heat energy coming from any discharge within the reach in B.T.U./hr.

Q_{BR} = the energy radiated from the water body to the atomosphere in B.T.U./sq.ft./hr.

Q_E = the heat energy transmitted to the atmosphere by evaporation in B.T.U./sq.ft./hr.

Q_C = the heat energy conducted to the air above the water surface in B.T.U./Sq.ft./hr.

A = the surface area of the reach in sq. ft.

Only those phenomena assumed pertinent to the behavior of the system are allowed to enter the expression.

To observe the meaning of this relationship (equation 3.1) it can be seen that when Q_H, the heat input rate, is positive (+) that is:

$$(Q_{NR} + Q_{HD} / A) > (Q_{BR} + Q_E + Q_C) \qquad 3.1.1$$

the rate at which heat is lost to the atmosphere is less than the natural and artificial heat addition and heat is being stored in the stream flow thereby raising its temperature.

When Q_H is negative (-) that is:

$$(Q_{NR} + Q_{HD} /A) < (Q_{BR} + Q_E + Q_C) \qquad 3.1.2$$

the rate of heat loss to the atmosphere is greater than the natural and artificial heat addition and heat is being removed from storage in the streamflow thereby lowering its temperature.

When Q_H is zero (0) that is:

$$(Q_{NR} + Q_{HD} / A) = (Q_{BR} + Q_E + Q_C) \qquad 3.1.3$$

the rate of heat entry equals the rate of heat dissipation to the atmosphere so the streamflow temperature remains unchanged.

Similar conditions can exist whether or not an artificial heat source is present.

To facilitate a more accurate picture of temperature variations below a thermal discharge the reaches should be made particularly small below this point.

The heat input to the reach, HI, is given by:

$$HI = Q_H \cdot A \cdot t, \text{ in B. T. U.} \qquad 3.2$$

where,

Q_H, A as previously defined

t = travel time through reach in hr.

The water mass travelling through the reach in t hours which is capable of absorbing the heat input, HI, is given by:

$$WM = Q_F \cdot \tau \cdot \rho, \text{ in pounds mass} \qquad 3.3$$

where,

Q_F = the average flow rate through the reach in c. f. s.

τ = $3600 \cdot t$, the travel time in seconds.

ρ = unit weight of water in lb/cu. ft.

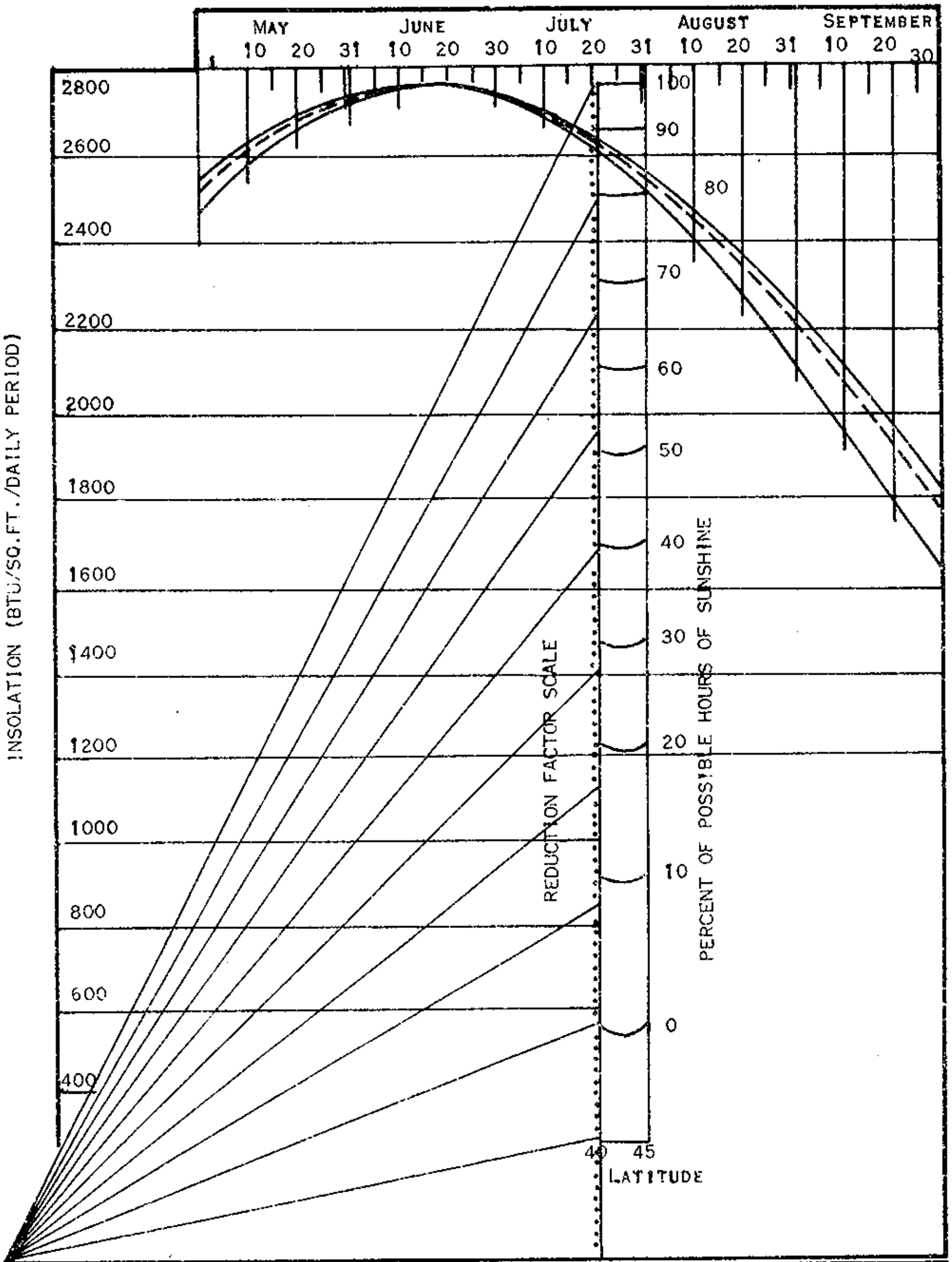
Finally, the temperature changes, ΔT, through the reach is given by:

$$\Delta T = \frac{HI}{WM}, \text{ in degrees Fahrenheit} \qquad 3.4$$

To facilitate the computational method which will be used, points at which either a heated discharge or a tributary enter will be designate a boundary between study reaches. This will aid later when considering the effect of flow augmentation upon temperature patterns.

In order to begin a sequence of computations yielding successive temperature changes down a watercourse, the temperature of the water entering the top of the first reach must be known. In addition, the maximum solar radiation possible under clear sky conditions for a daily period must be determined (a known, fixed quantity), the cloud cover measured, estimated, or predicted, the reflectivity-a function of solar altitude, and shading estimated from observations are all necessary to determine the net natural energy input, Q_{NR}, to the reach.

The maximum quantity of solar energy which could be expected is determined from the results of a study[33] carried out by the U. S. Weather Bureau in 1954. Extensive radiation measurements were used to construct a nomograph from which insolation, as a function of position on the earth, time of the year, and percent of possible sunshine, can be extracted. (See Figure 3.2). Subsequently this nomograph was used to create a two-dimensional array of radiation values which would be experienced at latitude 42.0 N, approximately the state line between the states of Connecticut and Massachusetts.



SEASONAL CORRECTION TO REDUCTION FACTOR

MAY	JUN	JUL	AUG	SEP	PERCENT OF POSSIBLE HOURS OF SUNSHINE
-1	-1	-1	-1	-1	70
-1	-2	-2	-1	-1	60
-2	-2	-2	-2	-1	50
-2	-2	-2	-2	-1	40
-2	-3	-3	-2	-1	30
-3	-4	-3	-3	-1	20
-3	-4	-4	-3	-2	10
-4	-5	-5	-4	-2	0

Figure 3.2 Nomograph to Determine Gross Radiant Energy Input to a Water Surface (From Harmon, 1954)

(A printout of this array is included in Appendix II.) It was felt that this would approximate, well enough, the radiation intensities experienced throughout the Connecticut River Basin. The array is 153 days (May-Sept.) in one direction and 11 units (0-100% of clear sky values) in the other direction. Given, then, the day-number during this summer period and the extent of cloud cover in tenths a value of radiation intensity striking a water surface can be found.

To facilitate extending the capabilities of the mathematical model to include the prediction of stream temperatures, some techniques of random number development are used to establish different degrees of cloud cover. More specifically, the amount of cloud cover, in tenths, will be ascertained by generating whole numbers of random magnitude ranging from 0 to 10 inclusive. This is done with the following formulae:

$$M_{n+1} = \text{last two digits of } (M_n \cdot 41) + 3, \; n = 1, \infty \qquad 3.5$$

where,

M_n, M_{n+1} = a modulus of magnitude varying from 00-99

M_1 = a number specifically chosen which will not cause the series to repeat, $M_1 = 31$

and,

$$R_{n+1} = \text{integer portion of } ((M_{n+1} + 1) \;/10) \qquad 3.6$$

where,

R_{n+1} = a random number of magnitude varying from 0-10

M_{n+1} as previously defined.

A uniform distribution is developed, but any distribution can be created if proved more realistic. These formulae were so established to expedite computer techniques which will subsequently be applied.

An assumption upon which this model is based is that a parcel of water may be observed as it traverses the watercourse and any changes in its character will denote character changes in the immediate area of the parcel. The immediate area is designated as the reach in which the parcel is located. This aspect of the model necessitated the creation of a mathematical procedure which would track the sun's position in relation to the parcel's position. Earliest attention is placed on the parcel, with the absolute time of enter and exit of the reach under study of prime importance. The time to traverse the reach is obtained from a knowledge of flow rates and of a flow-velocity relationship. The average of computed velocities at the boundaries of the reach when divided by the length of the reach yielded the time increment sought.

With this information available, the track of the sun can be determined, knowing in addition the initial position of the sun and the day of the year. If this is the first reach, the initial position may be assumed, but beyond this it is dependent upon the sun's movement in the previous reach. Figure 3.3 will help clarify some of the ideas involved. Basically, a negative cosine curve describes the sun's motion through a daily cycle. The objective is the creation of

Definition Diagram for Calculating the Reduction Factor for Radiant Energy Striking the Water Surface During Reach Travel Time

Example shows details of determining the factor for the 2nd reach on June 21st

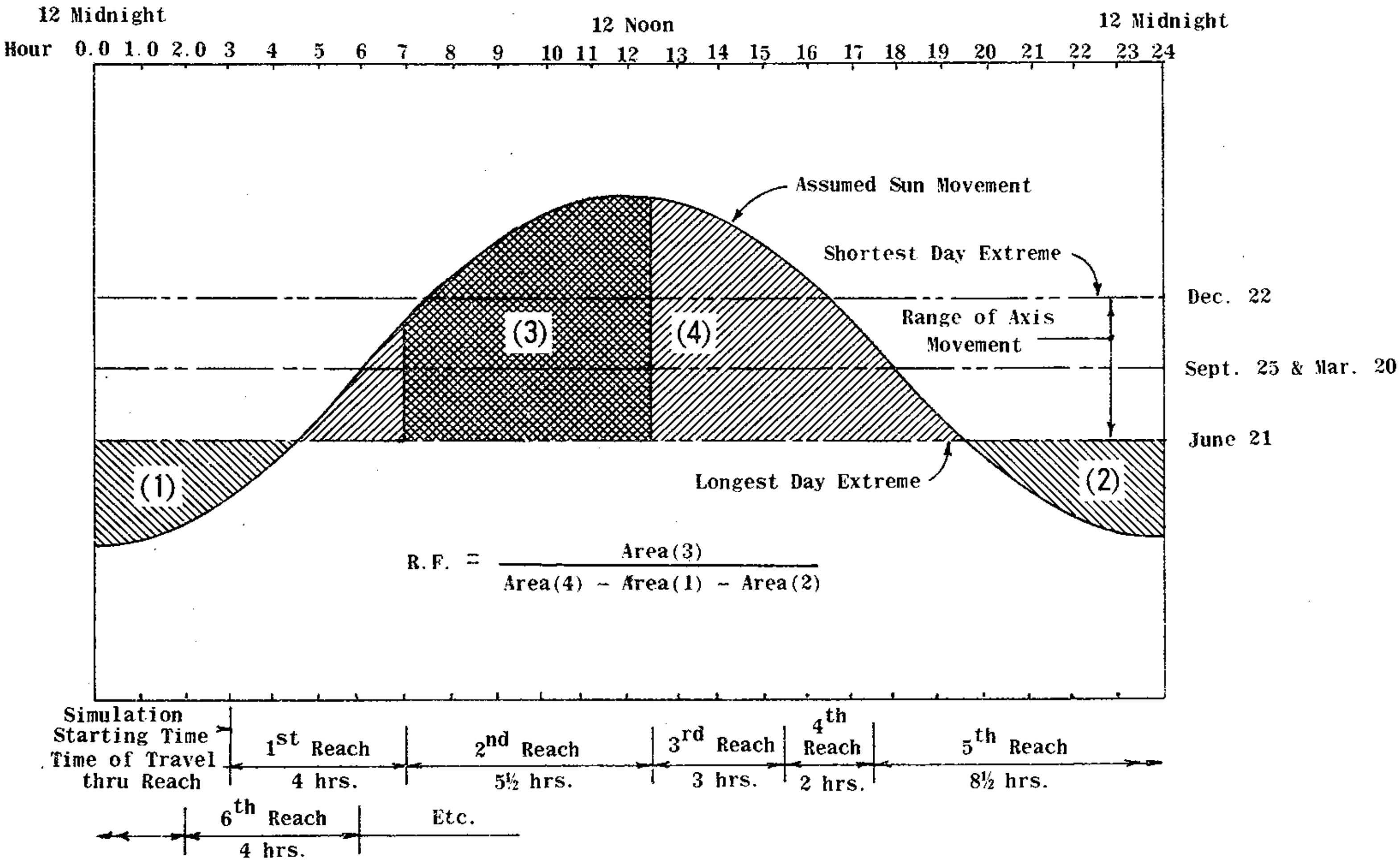


Figure 3.3 Definition Diagram for Calculating the Reduction Factor for Radiant Energy

another reduction factor to be placed on the gross radiation input.

The reduction factor is defined as the ratio of the net area under the curve between the times of entry and exit of the reach to the total positive area under the curve. In other words, the maximum possible quantity of radiant energy which the water surface could receive is reduced in proportion to the ratio of the period of time it does receive energy to the period of time it could receive energy.

Ultimately this factor is applied along with the others previously described to determine the net natural energy input to the reach.

Reflectivity and shading will be accounted for the in the adjustment of the model when applied to a specific problem. These specific model adjustments will be discussed in general in a section to follow.

Artificial heat ejections to a stream are obtained from design data. Usually available in terms of a temperature rise in the by-passed flow, the information may be translated to a loading rate, B. T. U. /hr., if necessary.

Back radiation, evaporation, and conduction are computed as described in the previous sections.

Heat energy advected into and out of the reach under study is not directly accounted for in the computations but is included when a temperature datum is established relating temperature in one reach to that in the next.

3.5.1. MODELLING THE EFFECT OF RUN-OF-THE-RIVER IMPOUNDMENTS

Water temperatures may also be subject to the influences which run-of-the-river impoundments may exert. As was indicated earlier, work is currently under way which could yield information regarding these influences and which should facilitate the prediction of water temperatures leaving an impoundment. In order that a model can be completed at this time, it will be assumed that reservoirs will cause no change in the temperature of the flow passing through them. When the necessary work regarding the specific effects is completed, the model can be easily modified to account for them. The temperature effect of an impoundment, for the purposes of inclusion in this model, will most likely be given in terms of reservoir volume, inflow and discharge rates, inflow characteristics, depth of withdrawal, and time of the year.

3.5.2. MODELLING THE TEMPERATURE ENVIRONMENT WHERE DISCHARGES ARE SUBJECT TO DIFFERENT CONDITIONS OF MIXING

Earlier in this paper four possible conditions of mixing which could be assumed to exist at and below a discharge point were reviewed. Each describes a different form of the well known, heat plume. Briefly, the discharge may (1) mix completely with the stream flow, (2) stratify vertically, (3) stratify horizontally, or (4) stratify both vertically and horizontally. One mode is usually chosen and assumed constant until sufficient heat energy has dissipated and the plume loses identity.

Different modes of mixing can be approximated by combining these conditions in different degrees. For instance, with the aid of the computer and its associated techniques, a reach can be broken up into many small increments between which the mode can be altered. If the increments are made small enough and the combination and degree of the modes is varied in some predetermined manner, mixing can be modelled. As an example consider the following hypothetical case; boundary conditions specify that at the discharge point the effluent occupies one-third the depth and one-tenth the width of the stream, at 100 feet downstream 1/3 and 3/10 respectively, at 200 feet 1/3 and 4/10 and so on. The 100 foot reach may be broken down into, say, 10 foot reaches with either the vertical stratification or horizontal stratification or both varying linearly from one sub-reach to the next. Such a procedure will in effect establish a mode of mixing.

In that the conditions are not presented as functions of known variables, such as flow velocity or bottom roughness, no mathematical relations can be established by which the effect of mixing is included in the mathematical model. For simplicity, each of the four conditions could be taken individually and in different degrees.

3.6 MATHEMATICAL MODEL ADJUSTMENT

Each mathematical model which is fabricated must be altered to correlate, as well as possible, its output with actual conditions. This approach is necessary as a result of several weaknesses. First, our inability to include every variable into the mathematical model introduces error. The second weakness concerns data availability. In most instances, sufficient data necessary to evaluate a model which includes only the most basic parameters is difficult and expensive even with modern equipment. To supply additional data then, may be an impossible task. For these reasons it has been found expedient to rely on specific model adjustments in an attempt to account for certain unknowns.

3.6.1. SOLAR RADIATION SHADING: In that solar radiation is the main source of heat to the water body, any change in the intensity or duration of exposure of the water surface will have a pronounced effect upon resulting temperatures. Therefore, shading from trees and cliffs and surface reflectivity must be investigated in order to establish a reasonable adjustment factor. Maps of the basin were reviewed and field inspections were executed to supply information upon which an estimation of this factor could be based.

An empirical relation was established which presents this adjustment factor as a function of river mile. Such a relation, it is believed, is justified considering the fact that as the stream widens in the downstream direction the reduction factor would be expected to increase, approaching unity. This is due simply to the physical geometry, comparing shading height to stream width.

The empirical relation established for the White River is as follows:

$$S_{RF} = 0.1 + RWL \left(R_{M(I)} + R_{M(M)} \right) / 2 \qquad 3.7$$

Where;

S_{RF} = Solar Reduction Factor

R_{WL} = Ratio of average shading factor to study area length.
= $0.4/51.7 = .00773$

R_M (I) = River mile at the head of the reach under study

R_M (M) = River mile at the end of the reach under study.

This relation yielded solar radiation reduction factors which varied in magnitude from .105 to .477. These are realistic and within acceptable ranges for this river.

3.6.2. EFFECTIVE SURFACE AREA OF TRANSFER: The previous section discussed the surface area over which incoming heat energy is effectively received. Similar consideration must be given to evaluate the effective surface area over which the mechanisms of heat transfer to the atmosphere act. An adjustment of this type must consider the flow regimes which may exist, that is, the areas which are effectively supporting an outgoing transfer of heat energy must be distinguished from stagnant ineffective areas. To make such a distinction not only must flow patterns be understood but also temperature patterns. This is an important indeterminate problem. The need to establish such an adjustment factor admits that the total water mass is not acting as part of the closed system, which is being analyzed, and consequently should not be incorporated into the heat balance relationship. Research with moving, highly turbulent western rivers has shown heat transfer rates for turbulent water bodies to be quite different than for lakes and impoundments. Similarly, the transfer coefficient should be expected to vary even over a small reach of stream where surfaces may vary from highly turbulent to limpid. With these comments in mind and with the experience or numerous computer simulations, attempts to establish a factor by which the gross surface area of the stream should be reduced were made. In that the surface was described by a long wedge-like trapezoid it was convenient to introduce the surface area reduction as a reduction to the variable trapezoid base. By trial and error procedures factors of different magnitude were inserted and the resulting profiles compared to observed profiles. A factor ranging in magnitude from .20 to .25 yielded a very good corrleation.

3.6.3. ADJUSTMENT OF METEOROLOGIC DATA FROM DISTANT COLLECTION STATIONS:

Very often a weather station will not be located in the immediate area under study. Therefore, data from the nearest station will have to be used and adjusted to account for the effect of geographic features which will cause changes in the different parameters. In the White River case study, however, data from the U. S. Weather Bureau at Lebanon Airport, which is near the perimeter of the basin, were believed to be representative of values experienced throughout the basin. If any of the data were to be adjusted it would be wind, to account for the gullies and protected nature of the river course, but the adjustment would be of a low order of effect on the resulting computations so it was, therefore, neglected.

CHAPTER IV

THE WHITE RIVER MODEL

4.1 INTRODUCTION

As has been emphasized throughout this presentation, there has been a tremendous deficit in the amount data necessary to implement temperature studies. The White River was chosen as a subject of study because there was an unusually large amount of temperature data available for the summer season of 1965. This was a result of special field studies which were aimed at measuring many water quality parameters among which were air and water temperature. Also, the river has not been subjected to artificial heating, the temperature readings taken, therefore, are representative of natural conditions.

4.2 GENERAL BASIN DESCRIPTION

The White River Basin, shown in Figure 4.1 with a drainage area of 712 square miles, all in Vermont, rises on the northeast slope of Battell Mountain of the Green Mountain Range in the Town of Ripton, Vermont, and flows east five miles to Granville, then south 19 miles through Hancock and Rochester to Stockbridge where it turns and follows a northeasterly course nine miles to Bethel. It then flows easterly seven miles to South Royalton, and finally southeasterly 18 miles, through the villages of Sharon and Hartford, to its confluence with the Connecticut River at White River Junction, Vermont. The White River has a total length of about 60 miles and a total fall of about 2,170 feet of which 1,600 feet are in its upper nine miles. The three principal tributaries are the First, Second, and Third Branches.

4.2.1 CLIMATOLOGY AND HYDROLOGY

The relatively high elevations of the Green Mountains have a marked influence on temperature, precipitation, and depth of snow cover in the White River Watershed. The basin undergoes extremes of cold and depth of snow as compared to average conditions in the Connicticut River Basin, of which the White is part.

The average annual air temperature of the White River Basin is about 41^{o}F. There is little variation throughout the basin due to its relatively small size. Average monthly temperatures vary widely throughout the year, from about 16^{o}F. in January and February to about 68^{o}F. in July.

The average annual precipitation over the entire basin is in excess of 50 inches. This high average is due to orographic influences as well as elevation. The distribution of precipitation throughout the year is rather uniform although somewhat heavier precipitation is experienced during the summer months.

Stream flow data has been published by the U.S. Geological Survey for two stations in the White River Basin, one at Ayre Brook and one at West Hartford. West Hartford is indicated as point number 2 on Figure 4.2. The records are rated as generally good to excellent

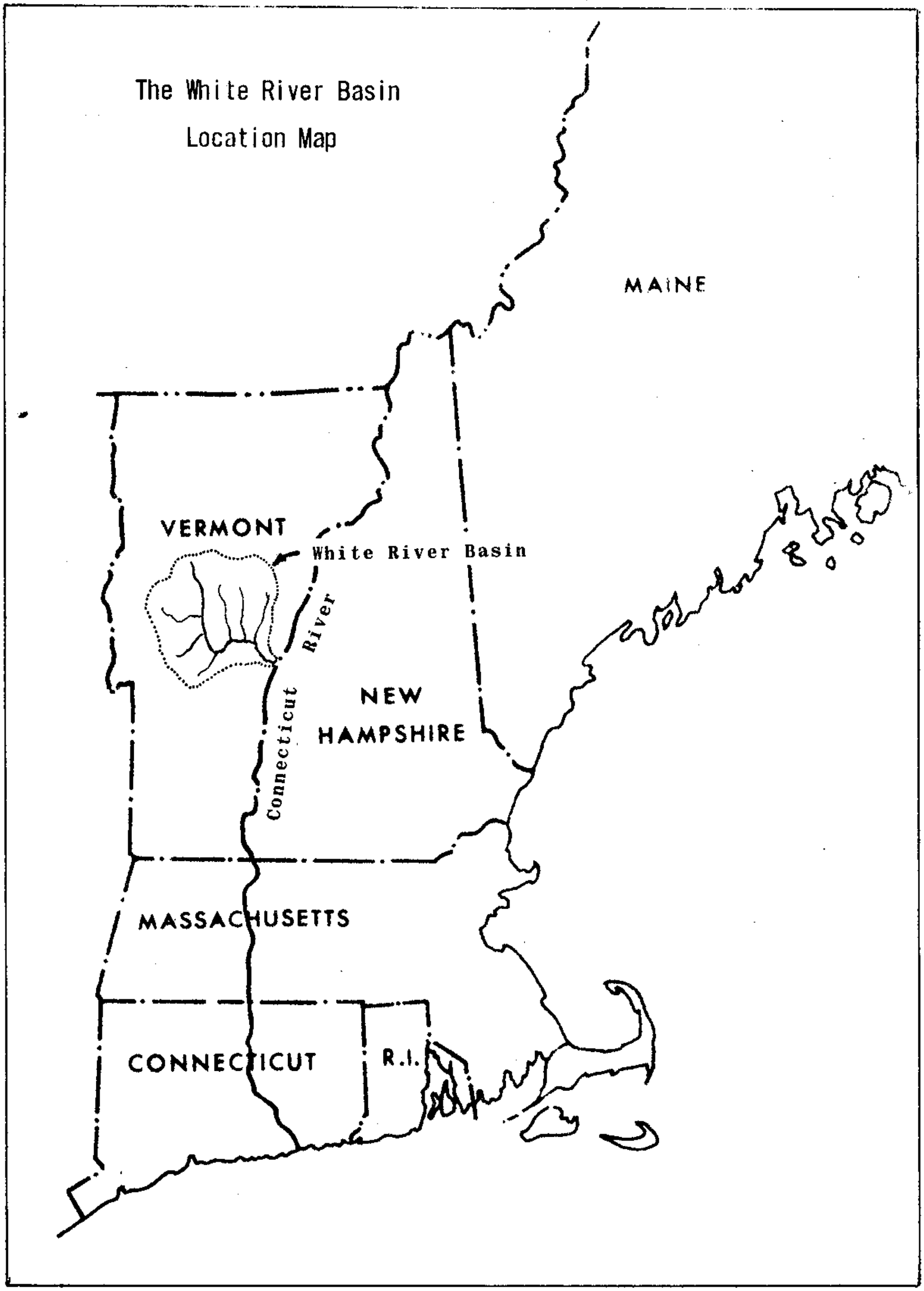


Figure 4.1 The White River Basin, Location Map

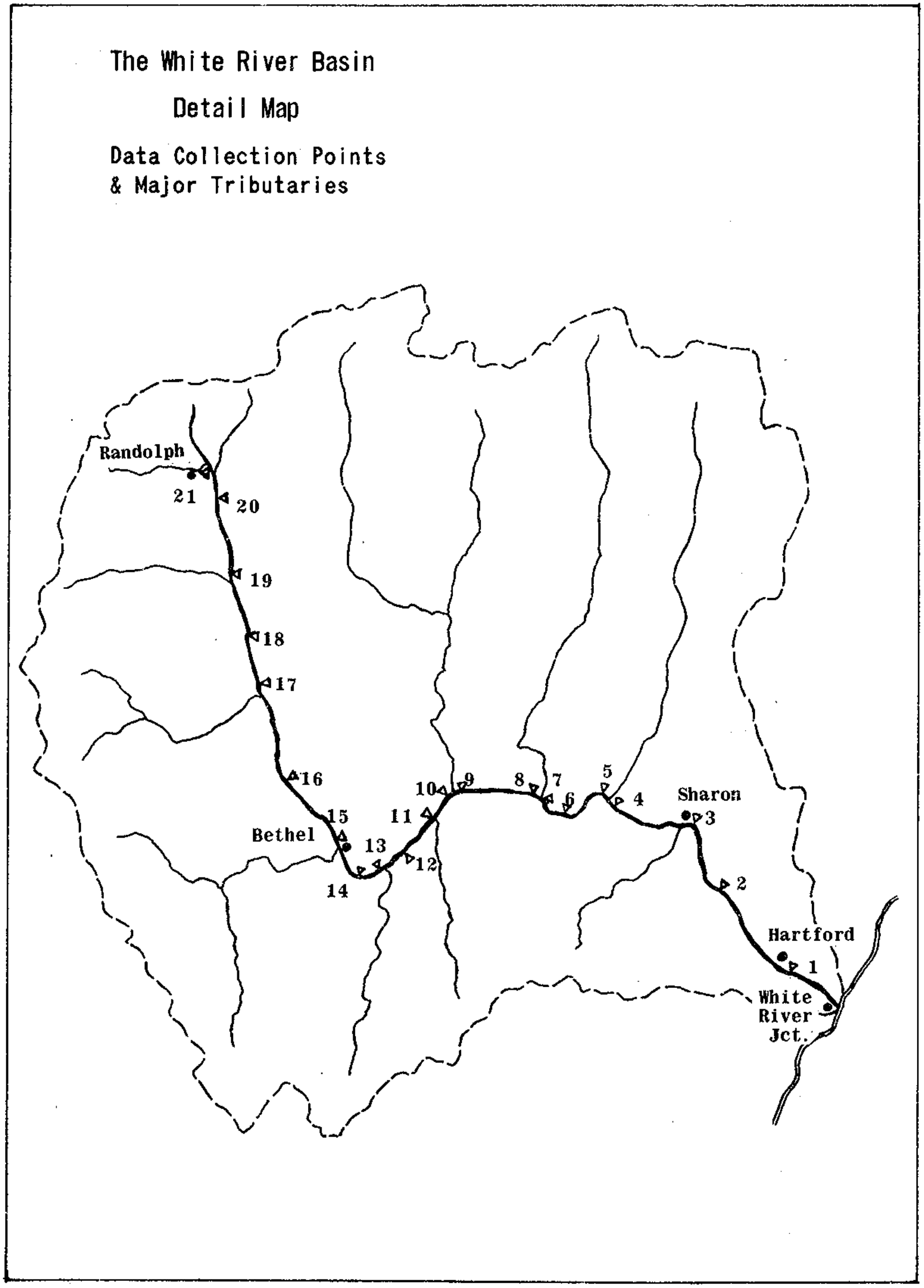


Figure 4.2 The White River Basin, Detail Map

(this includes the period of time with chich these studies are concerned) except during periods of ice when they are rated as fair.

The basin has an average run-off of over 40 inches (3.0 cfs/ sq. mi.) over the period of record. About 50% of the annual run-off occurs in the months of March, April, and May.

4.2.2 DATA SOURCES

Four primary sources supplied the data necessary to implement the simulation model. Water and air temperatures were made available from the Vermont Water Resources Commission; wind, relative humidity, wet and dry bulb temperatures, sky cover from the U. S. Weather Bureau at Lebanon Airport, Lebanon, New Hampshire; flow rates from the U. S. Geological Survey; and velocity-flow relationships from the Federal Water Pollution Control Administration.

The computer program which utilizes this data has a general arrangement as shown in Figure 4.3(a). The arrangement of the data in particular is shown in Figure 4.3(b). A print-out of the actual input data is found in Appendix C.

The collection and reduction of this data was aided by the use of an organizational device as described earlier. The utilized data status sheed is shown in Figure 4.4

4.2.2 TEMPERATURE PROFILES. Based on the temperature measurements

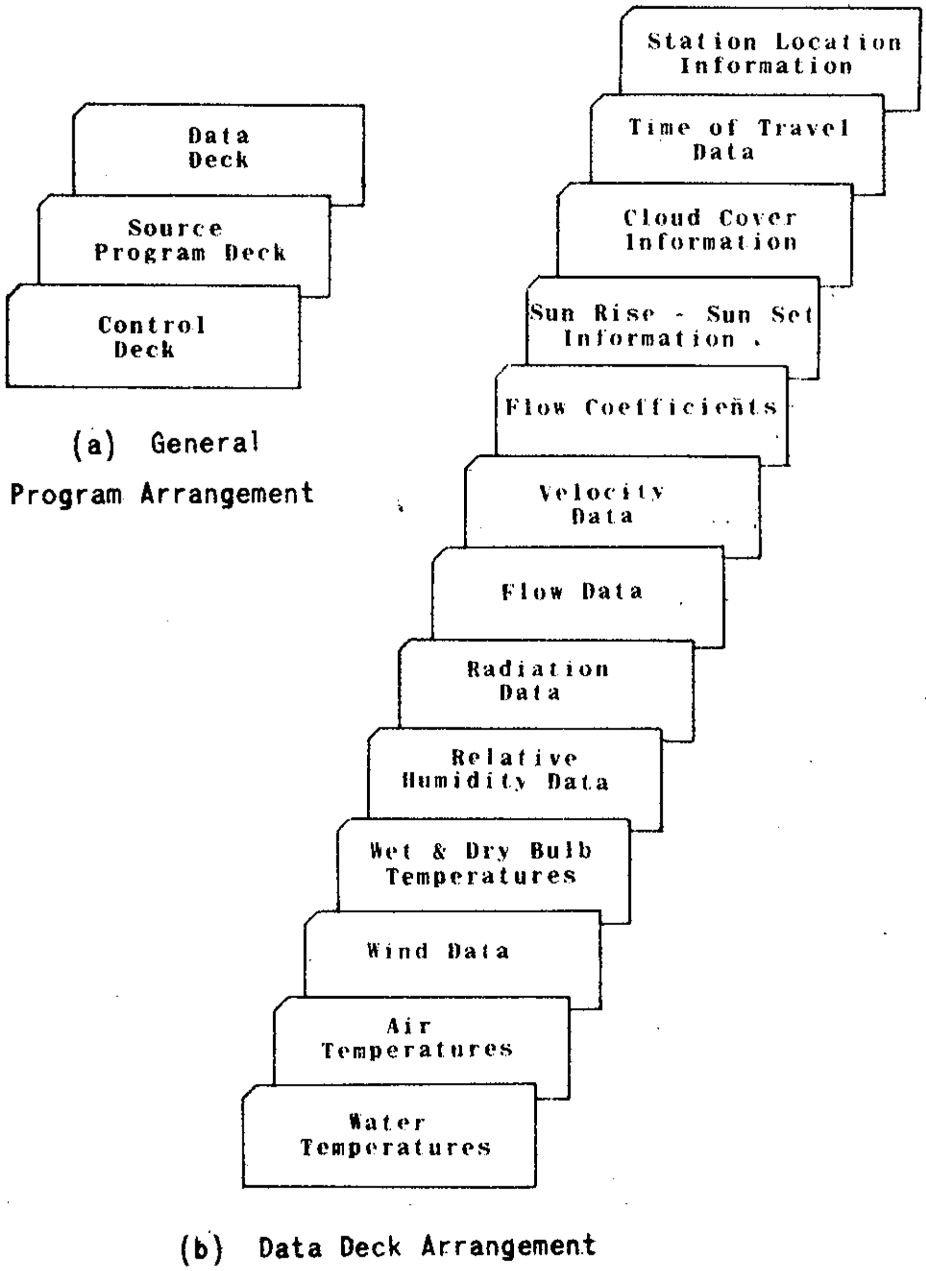


Figure 4.3 General Program and Data Deck Arrangements

INPUT DATA STATUS SHEET

STUDY TITLE: White River, Vermont

STUDY PERIOD: 5-65 to 9-65 | DATE: 9-68 | IN CHARGE: wgg

PARAMETER \ STATUS	Available from usual sources	Available from special study	Available thru field work of this study	Data estimated	Data not available	Data available on: magnetic or paper tape	Data available on: computer cards	Data in rough form, must be transcribed	Transcribed to cards	Transcribed to tape	Transcription complete	Data available
1. Water Temperature		✓						✓	✓		2·1·68	2·1·68
2. Air Temperature		✓						✓	✓		2·1·68	2·1·68
3. Local Wind	✓							✓	✓		2·29·68	2·29·68
4. Relative Humidity	✓							✓	✓		3·6·68	3·6·68
5. Dry Bulb Temperature	✓							✓	✓		3·6·68	3·6·68
6. Wet Bulb Temperature	✓							✓	✓		3·6·68	3·6·68
7. Dew Point Temperature												
8. Sky Cover				✓								
9. Solar Radiation				✓								
10. Atmospheric Radiation				✓								
11. Flow Rates	✓											
12. Stream Cross-sections												
13. Velocities				✓								
14. Time of Travel				✓								
15. Surface Area				✓								

Figure 4.4 Utilized Organizational Aid

available through the Vermont Water Resources Commission water temperature profiles were constructed, the results of which appear in Figure 4. 5. This information forms a datum toward which the simulation model results are directed.

4. 3 THE SIMULATION MODEL

The mathematical relationships previously developed in conjunction with certain mathematical techniques for choosing, analyzing and assemblying data formed the simulation model. These interdependent mathematical descriptions of natural phenomenon were then translated into Fortran IV computer language facilitating implementation on an IBM 7044/7094 II computer. A logic diagram and print-out of the computer program are found in Appendix B.

The model uses a variable length study reach, which in this case study was taken for simplicity to be the reaches between data collection stations. This approach resulted in twenty study reaches varying in length from .1 to 6. 3 miles. The values of the operating parameters were set equal to the average of values measured at the data collection point forming the head and foot of the study reach. A parcel of water is followed incrementally from one reach to the next, applying the heat balance relationships to determine the net change in temperature through each reach and which ultimately facilitates the construction of stream water temperature profiles.

Eleven simulation models were studied which tested different

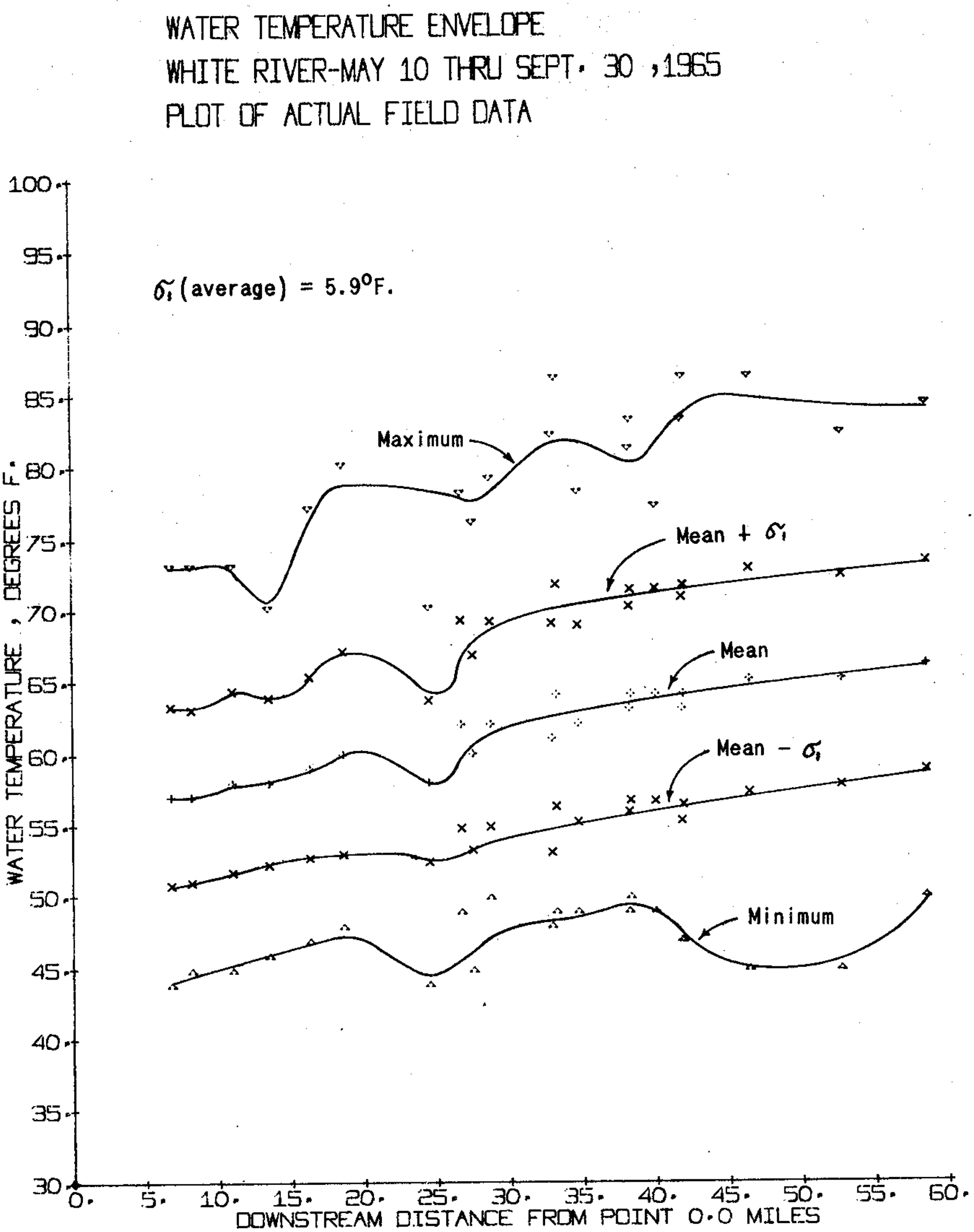


Figure 4.5 Water Temperature Envelope as Observed During Summer of 1965 assumptions and hypothetical uses of the stream water. The choice of locations of such facilities as might discharge waste heat or discharge stored water for low flow augmentation and dilution was arbitrary but was guided by a knowledge of population distribution and other criteria which would effect such locationing. In no instance was a realistically sized thermal discharge or cool water discharge used. This was a consequence of basin size, which obviously could not support the waste heat loads of a typical modern day thermoelectric station. The basin serves, then, only as a scale model. The waste heat discharges were, therefore, scaled down to an order of magnitude compatible with the stream flows experienced so that the developed output would have meaning. A schematic representation of the White River is shown in Figure 4.6. Also shown are the heat and cool water sources which appear in the various simulations.

4.4 THE MODELS STUDIED

4.4.1 SIMULATIONS OF NATURAL CONDITIONS

Adjustments of meteorologic and hydrologic parameters were necessitated in some instances because of local geographic influences. Estimations of these effects were accounted for in the computations by the modification of input data through routine of the computer program. The modifications are discussed in general in section 3.6, entitled, Mathematical Model Adjustments.

In the first attempt to simulate natural temperatures a moderate

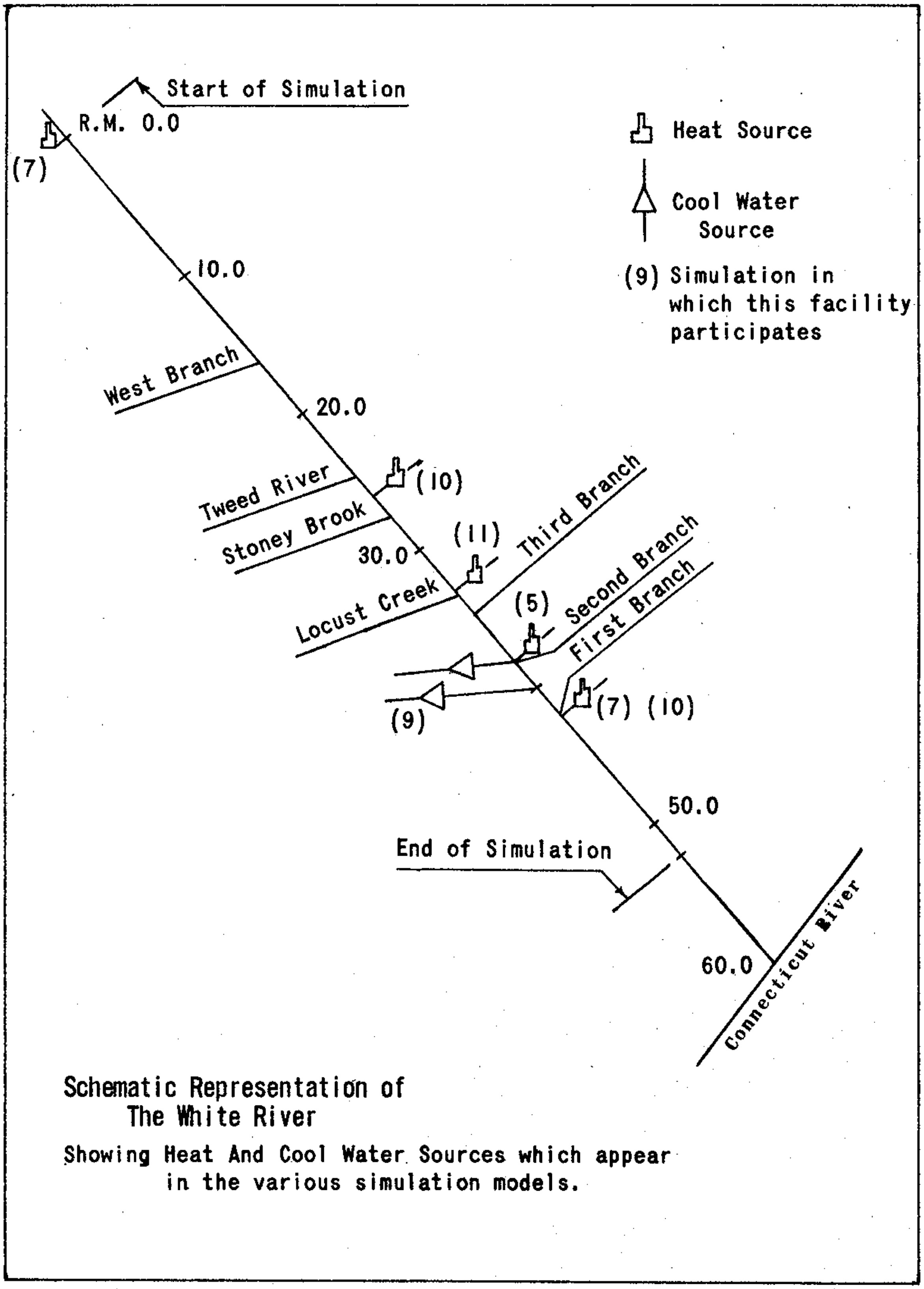


Figure 4.6 Schematic Diagram of the White River

adjustment was made to account for the effect of shading of solar radiation. The adjustment amounted to a reduction of 25%. The results of this simulation appear in Figure 4.7. Although the curve describing the mean stream water temperature is a good representation of observed temperatures (Fig. 4.5), the band of $\pm$ one standard deviation (σ_1) was believed to be too wide. The average value of σ_1 for this simulation was found to be 6.2°F. This band represents the range in which the mean value could be expected to fall 68% of the time.

Following an examination of portions of the White River it was decided that shading of radiant energy was actually greater than first estimated. A second simulation accounted for this increase by raising the reduction factor to 50%. The results appear in Figure 4.8. Most apparent is the narrower band established by $\pm\ \sigma_1$ which resulted, σ_1 (average) equaling 5.1°F.

This ability to observe the effect of changes in a single variable illustrates very clearly the strength of this problem solving technique. Also, a fact which emphasizes the advantage of the computer techniques employed is that a complete simulation required approximately 1.5 minutes of computer time. It was estimated that it would require 10 man-months to accomplish the same end.

Comparing the first two simulations to the surveillance data several observations can be made. The field temperature data, when collected, did not follow a spatial or temporal pattern which facilitated the following of a parcel of water downstream. Consequently,

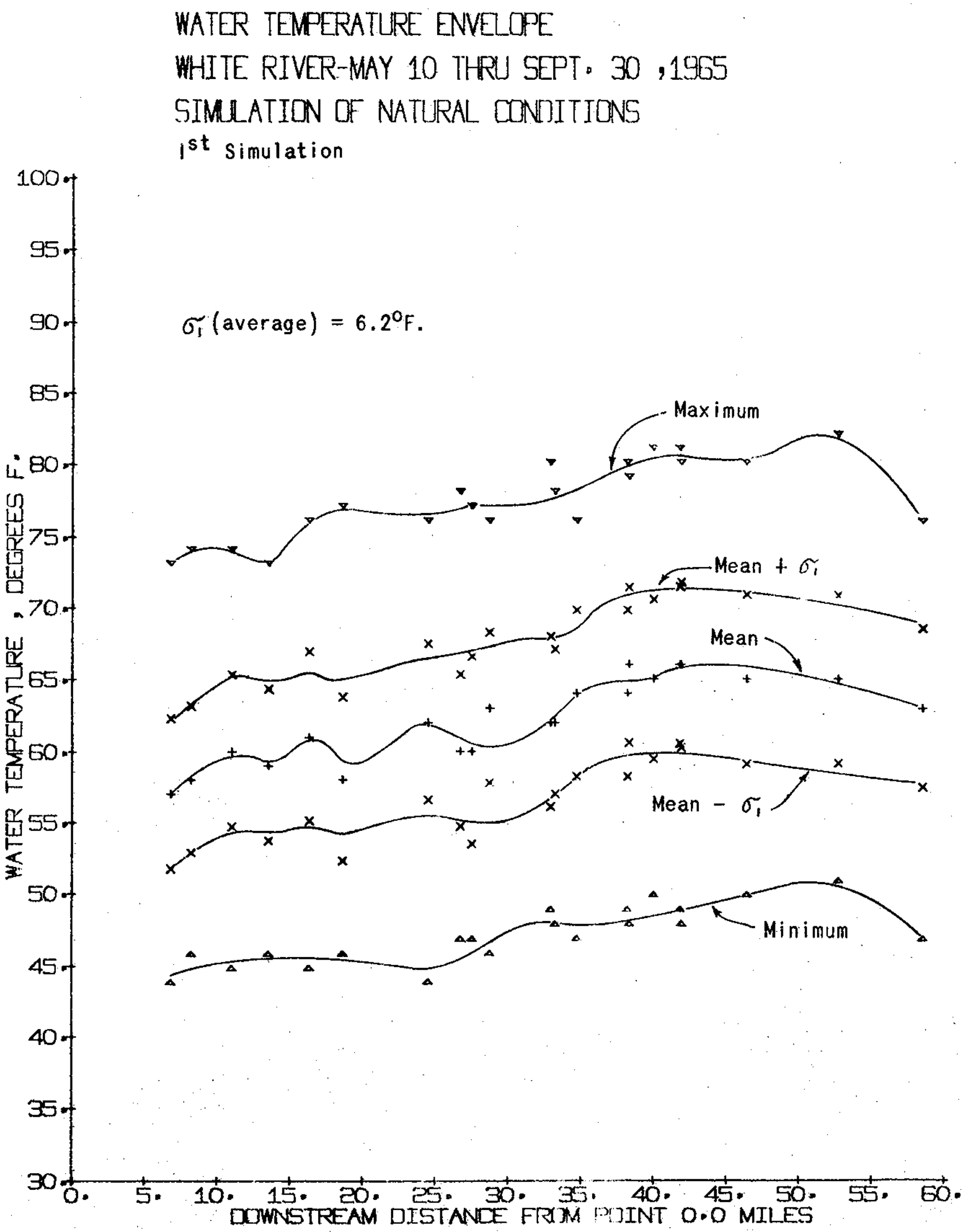


Figure 4.7 Water Temperature Envelope for First Simulation of Natural Conditions

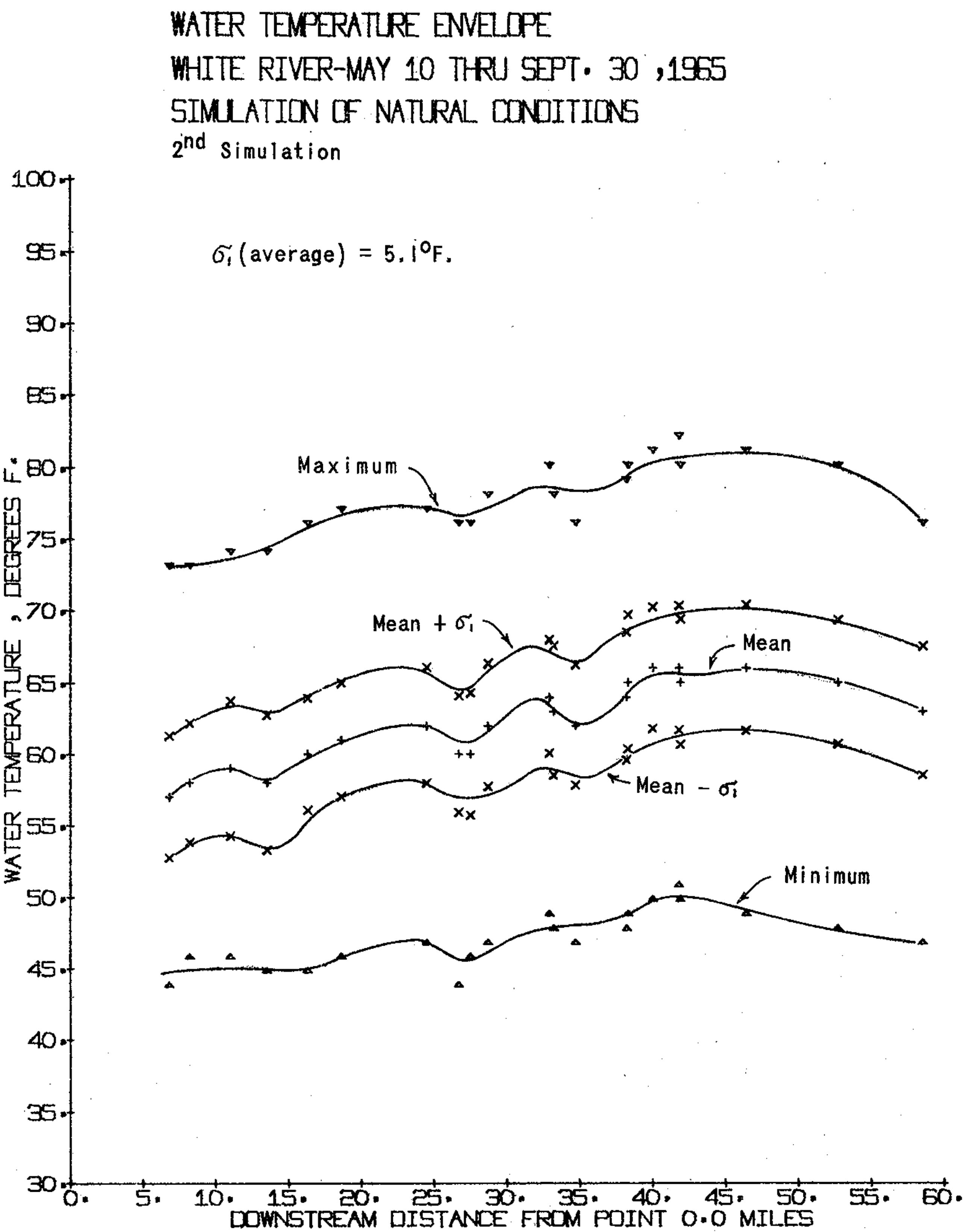


Figure 4.8 Water Temperature Envelope for Second Simulation of Natural Conditions the diurnal variation in the temperature of a parcel of water was not noticable. This would also account in part, for the fact that the standard deviation in the second simulation was actually smaller than that for the observed data.

The diurnal variation in temperature, however, can be seen in the results of the simulation because a parcel-following technique was used. The simulation results when plotted, therefore, suggest the cycle peaks. The diurnal variations become more pronounced when partial-period examinations were made. Depending upon flow rate, the time of travel varied from 3 to 5 days. This fact makes it difficult to draw much conclusion from the longer period studies because points of interest are obscured.

The sixth simulation, probably the best obtained, is summarized in Figure 4.9, where it is compared to the observed profile. This variation was created by changing the simulation starting time from 6.00 hrs to 3.00 hrs.

4.4.2 PARTIAL PERIOD SIMULATIONS

In order to create a more comprehensive understanding of temperature variation, the study period was broken into partial periods. This breakdown was based on stream flow, with two periods distinguished. The first period is represented by the first two mo ths of the summer period and the second by the last three months. These two periods are respectively characterized by comparatively high flow of spring runoff (average flow = 379.4 cfs) and low flow (average flow = 123.5 cfs).

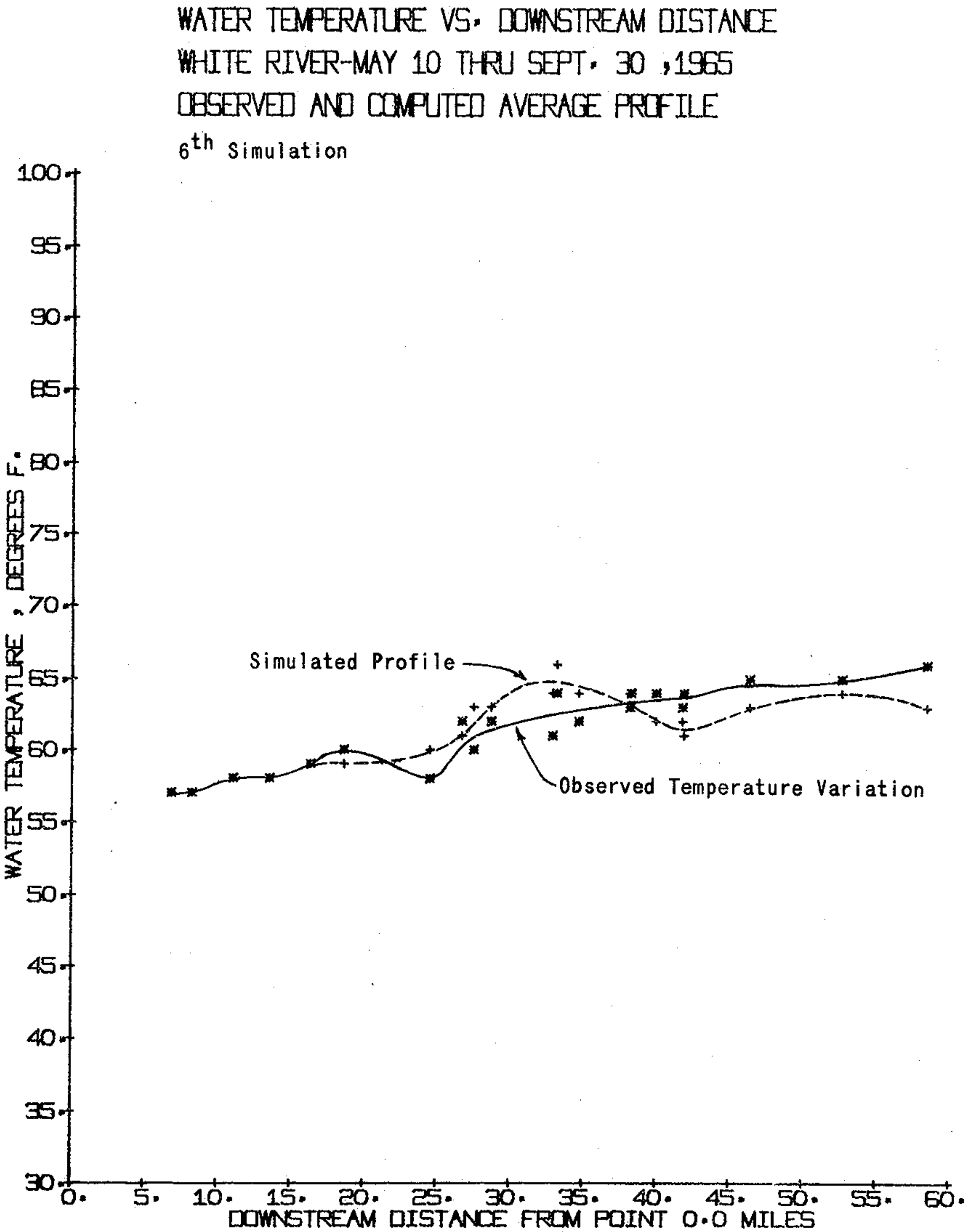


Figure 4.9 Observed Average Profile and Best Simulation Profile of Natural Conditions

The results of a simulation of the high-flow period is shown in Figure 4.10, the 4th simulation. More obvious than in earlier simulations is the peaking due to diurnal variations. The subdivision helped to clarify these peaks and also to reduce the distribution of computed values, which consequently yielding a smaller average standard deviation. Similar comments can be made of the 3rd simulation, one of low flow conditions, the results of which appear in Figure 4.11.

4.4.3 SIMULATIONS TO INVESTIGATE THE EFFECTS OF HYPOTHETICAL HEAT LOADS ON STREAM TEMPERATURE

With an understanding of natural variations of stream water temperatures at hand, artificial heat loads were imposed and the effects observed. The 5th simulation, the results of which are presented in Figure 4.12, applies an artificial heat load at 38.0 miles from the simulation starting point and 22.0 miles from the confluence with the Connecticut River. The withdrawal and discharge was set arbitrarily at 150 cfs, which experiences a temperature increase of 13°F. This is approximately equivalent to a heat discharge rate of 120,000 BTU/SEC. It was also assumed that complete mixing occured at the discharge. The results indicate a temperature rise of about 5°F which returns to near natural conditions within about 17 miles. This can observed and seen in Figure 4.13 which shows only the average profiles for simulated conditions. This exercise, it is believed, demonstrates support of the hypothesis that artificial conditions can be superimpose upon natural conditions to yield a realistic picture of resulting conditions.

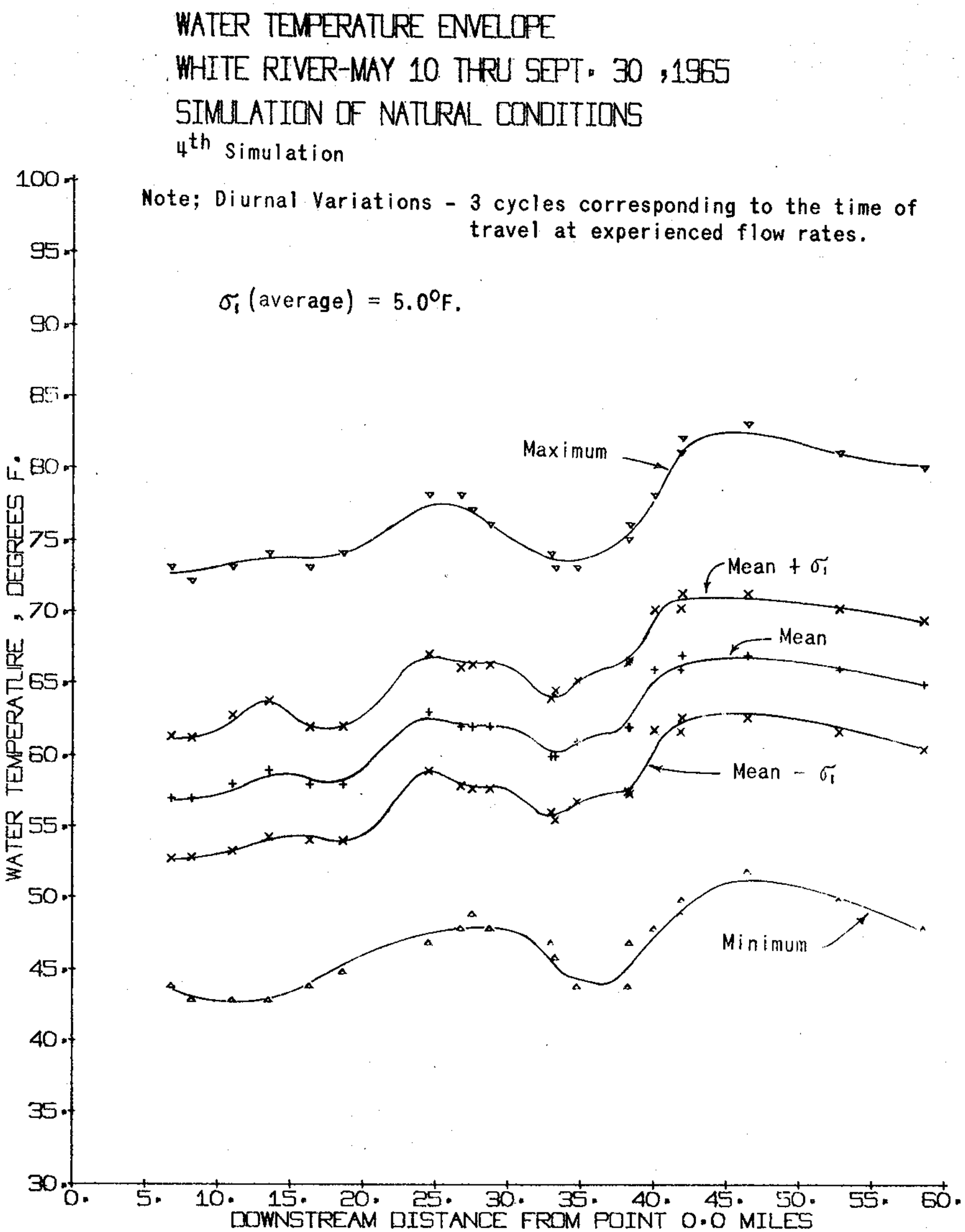


Figure 4.10 Water Temperature Envelope for a Simulation of Natural Conditions for Days Near the Beginning of the Study Period

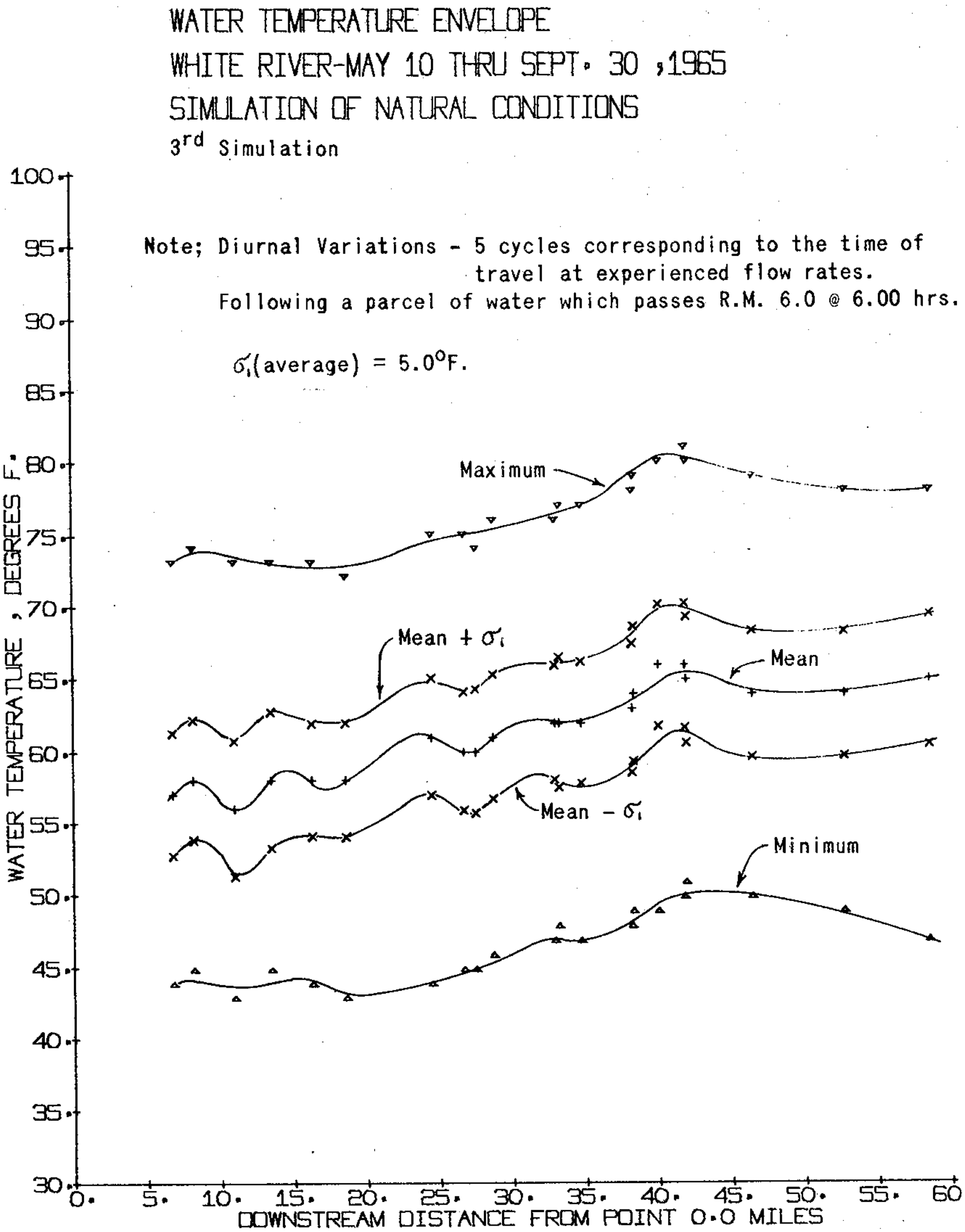


Figure 4.11 Water Temperature Envelope for a Simulation of Natural Conditions for Days Near the Middle of the Study Period

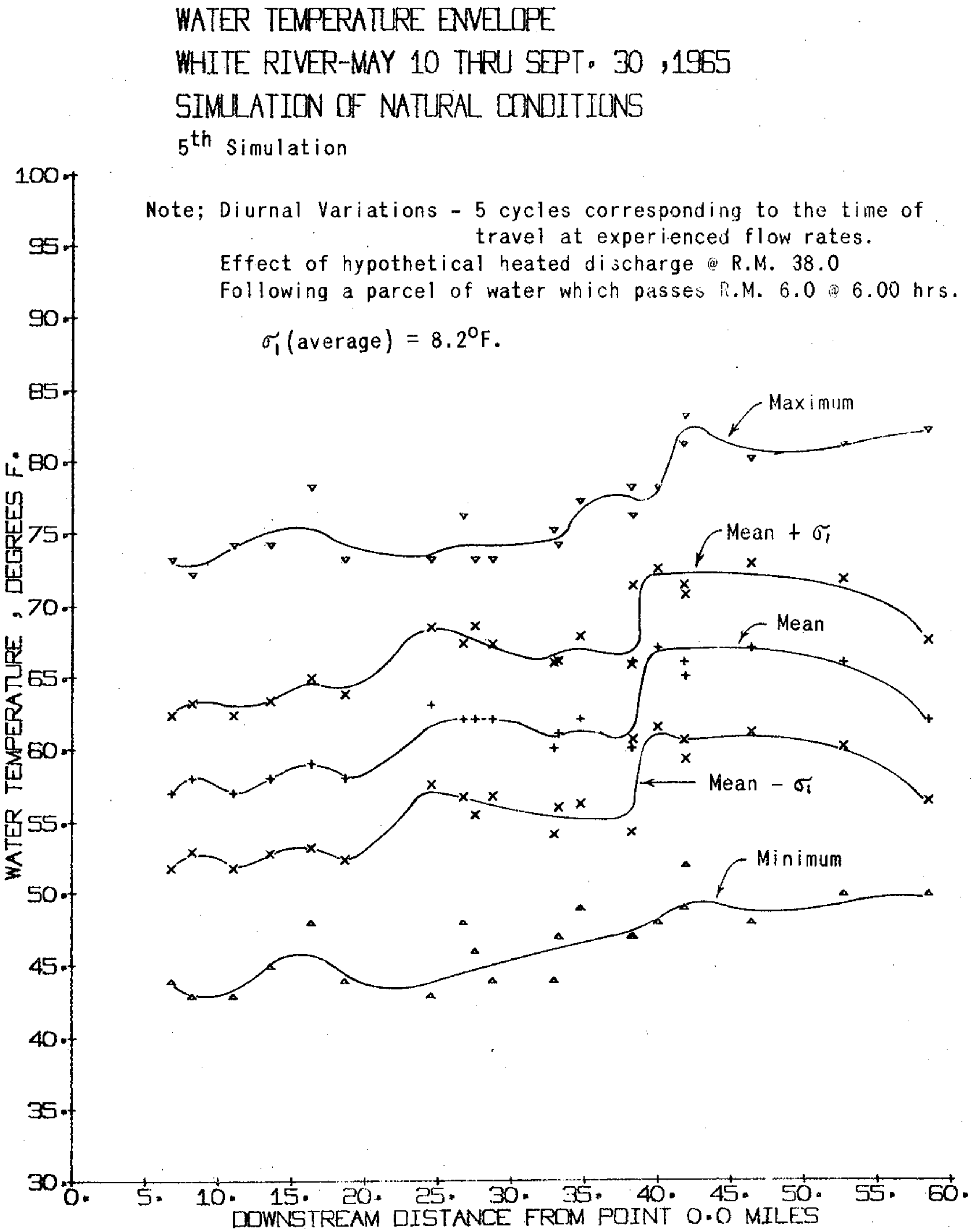


Figure 4.12 Water Temperature Envelope for a Simulation with a heat Source for Days Near the Middle of the Study Period

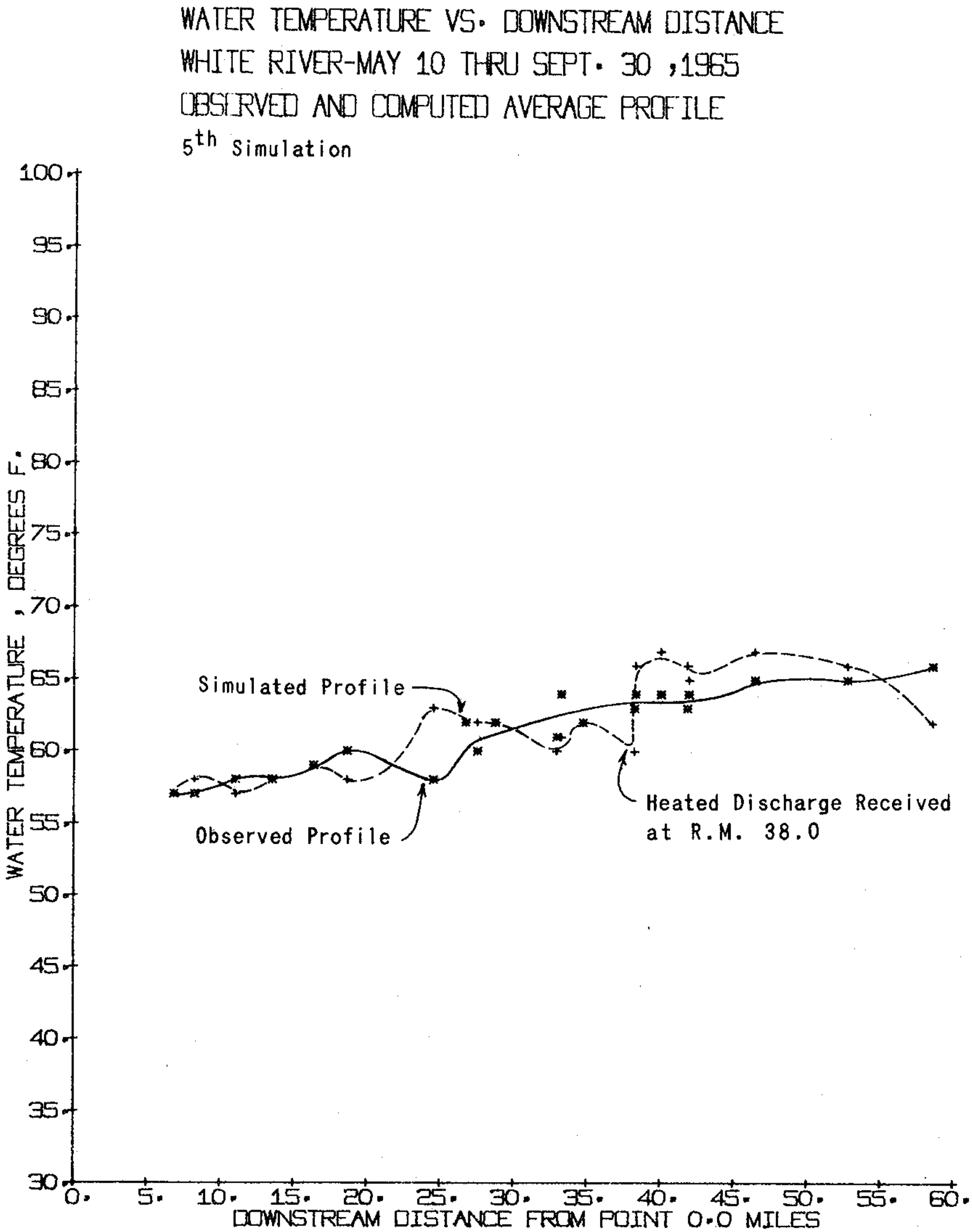


Figure 4.13 Observed Profile and Simulated Profile with a Hypothetical Heat Source

The 7th simulation (Figure 4.14) considered a hypothetical discharge at river mile 6.0 measured from the beginning of the study area. A discharge consistent with the small average flow experienced was introduced creating an increase in the mean stream water temperature of approximately 10°F. In view of the fact that this is an area in which the stream experiences a rapid fall in elevation, with accompanying turbulent flow, it is not unreasonable to expect a sharp fall in the profile curve. The area also experiences comparatively lower air temperatures and higher winds than other portions of the basin. These facts support the rapid fall of temperature to natural levels, which occurred within about 5.0 miles.

The 8th simulation (Figure 4.14) introduces the same thermal load as used in the 5th simulation except 5.0 miles further downstream, at river mile 42.0. In this case temperatures returned to normal within about 10 miles.

The 11th simulation (Figure 4.15) introduces a 240,000 BTU/Sec discharge at river mile 33.0. This created about a 10°F. increase in temperature which returned to near normal conditions within about 11 miles.

4.4.4 SIMULATIONS TO INVESTIGATE THE EFFECTS OF HYPOTHETICAL COOL WATER DISCHARGES

As mentioned previously, an important function of a multi-purpose reservoir should be the control and enhancement of stream water temperatures in downstream reaches. It must be pointed out, also

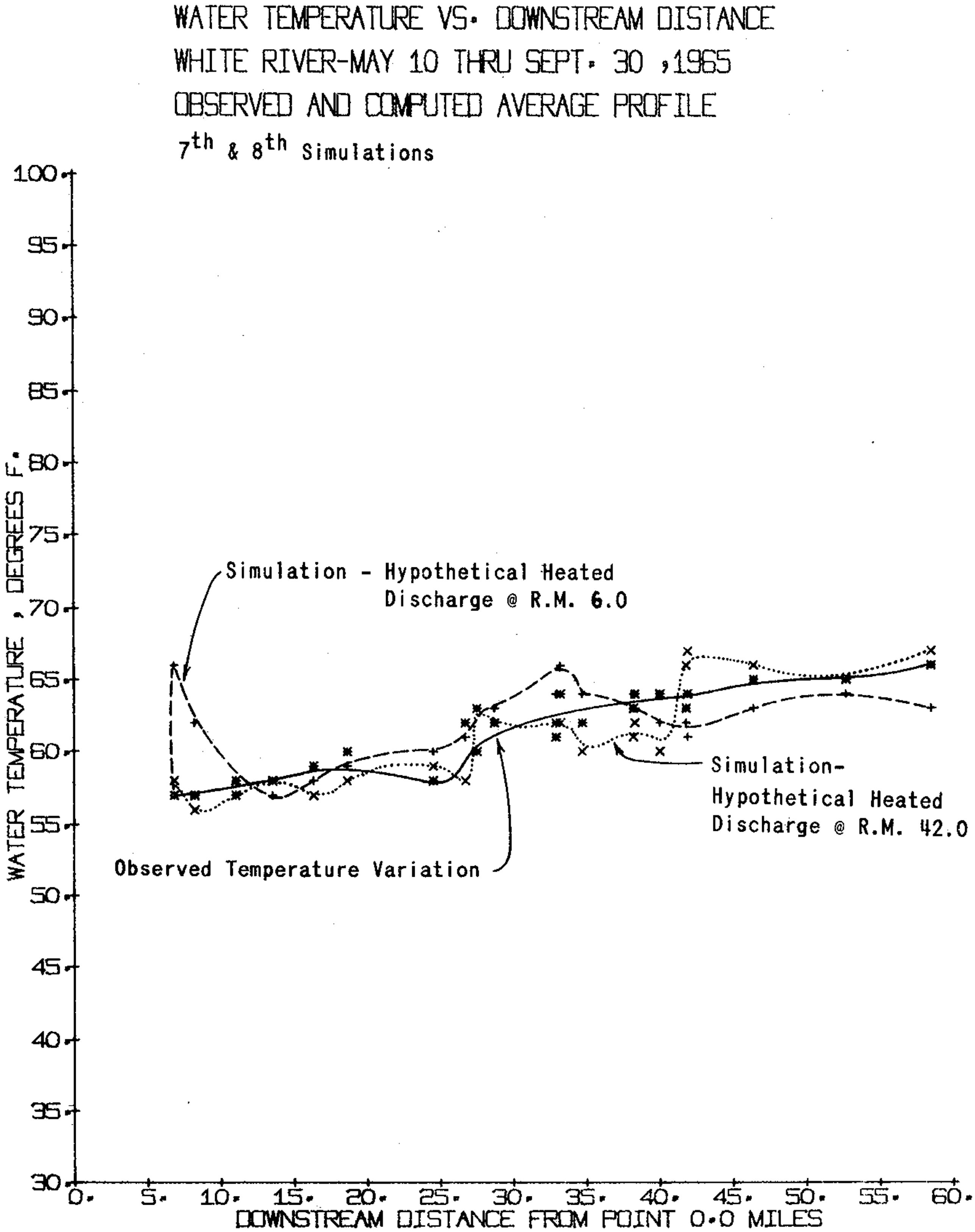


Figure 4.14 Observed Profile and Simulated Profiles with Hypothetical Heat Sources

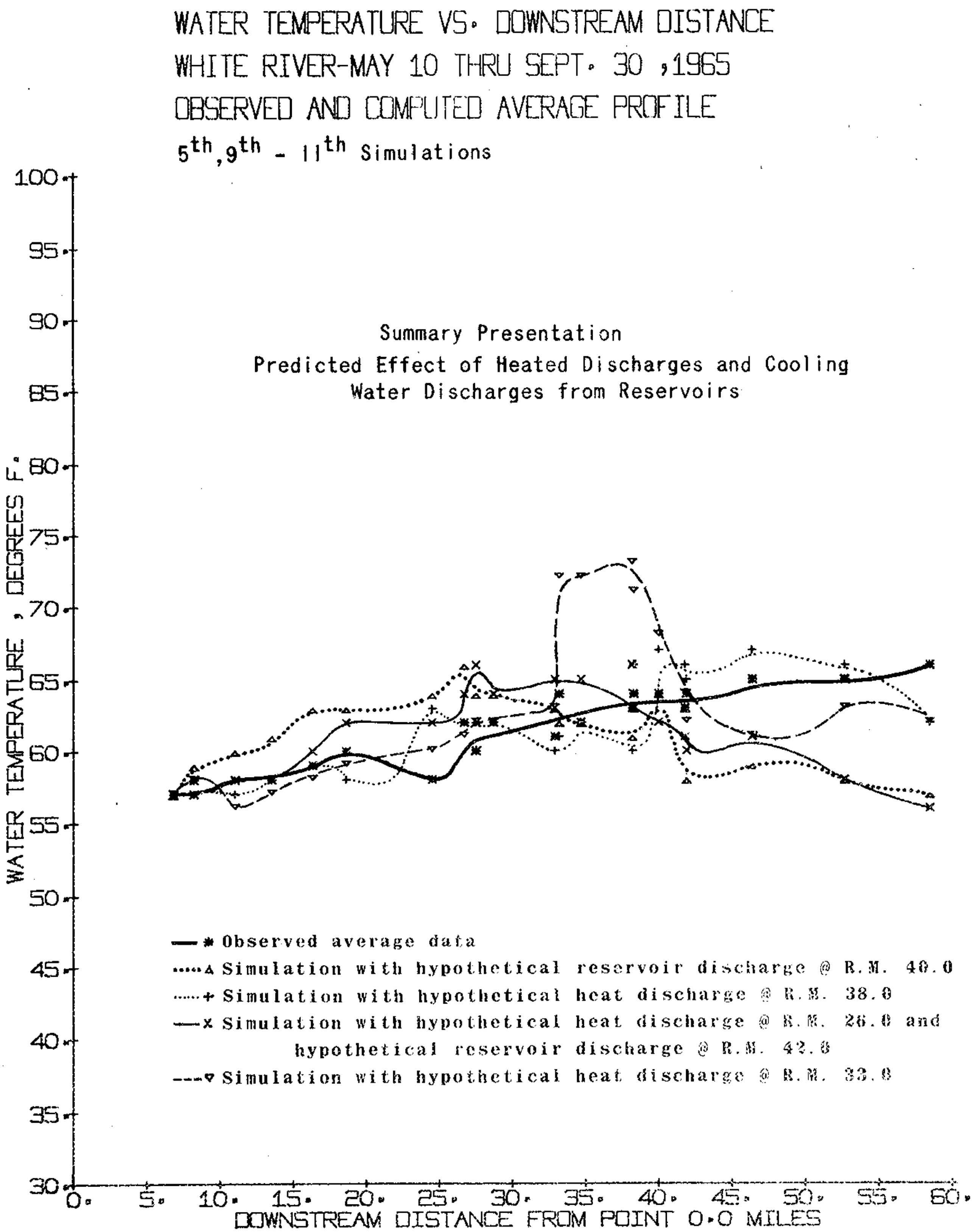


Figure 4.15 Results of Simulations with Hypothetical Heat Sources and Cool Water Discharges

that there are no methods existing which facilitate evaluation of their overall effect, in this regard. This void in our water resource development skill will be filled, in part, by the technique suggested herein. To this end, the effects of hypothetical cool water discharges were analyzed using the very same heat balance model as applied to heated discharges.

Several reasonable assumptions were made. First, the dam has multiple outlets which permit the discharge of water from different layers at different temperatures. These will mix to the desired temperature. Of course, in the event that the temperature of the water from a particular outlet is that desired, then there need be no mixing. This further assumed that either an understanding of the temperature regimes within the reservoir exists or an effective temperature monitoring system exists or both exist and can supply the necessary information upon which operation decisions can be made.

It was further assumed that these discharges are available immediately at the predetermined temperature to the main stream under analysis. This is not unreasonable in view of the fact that although a reservoir may be some distance up a tributary, this very technique, if verified, can be applied to determine any change in temperature from the point of discharge to the point of confluence with the main stem. Finally, it was assumed, as with heated discharges, that the discharge mixed completely with the main stream flow.

The 9th simulation displayed in Figure 4.15, considered a reservoir discharge entering at R. M. 40.0 at a flow rate of 130 cfs and temperature of 42°F. This resulted in approximately a 5°F temperature drop which was not at all unreasonable recognizing that the average flow over the study period was 265cfs.

The 11th simulation considered the effect of both hot and cold water discharges, however there was no interaction because of their wide separation.

Discussion now centers on the effect of the reservoir discharge. The temperature of the discharge was set at 42°F., as in the previous example, and the volume rate of flow at 60 cfs, entering the main stream at R.M. 42.0. The result was a much less obvious depression in temperature than experienced in the previous example. However, it is consistent with regard to the relative proportions of flow. In this simulation, as in the last, the temperature, after a short stable period begins to drop off abnormally. Several reasons for this occurrence may be suggested.

First, it is known that in both simulations the same climatological conditions existed because of the pseudo-random technique used. Therefore, since there are no other variables of real consequence it seems evident that the same condition or phenomenon is responsible for the abnormal drop off in temperature. An examination of the cloud cover data developed showed that there was an unexpected high frequency of days with 50% or more cloud cover. This, it is believed, was cause enough for the occurrence. At this point it was realized that the same tailing-off occurred in all the simulations. This further supported the hypothesis.

4.5 DISCUSSION OF MODEL STUDY RESULTS

Based on the results of the mathematical simulations a number of conclusions can be drawn. First, and probably most important, is the fact that the energy balance approach to the solution of river temperature problems is shown to be applicable and is in fact a method of great strength.

The success of the method is due, in a great part, to the detailed and accurate data. Although the acquisition and preparation of the data is an expensive, tedious and time-consuming process, it is emphasized once again that the success of the whole study effort is directly dependent on it.

Of equal significance regarding the success of the mathematical model was the selection of adjustment factors which exhibited a pronounced effect upon the resulting temperature profiles. A case in point is that of the solar shading adjustment factor which, when increased to a more realistic value, provided a more acceptable value of the average standard deviation of temperatures.

It must be emphasized that, analyzing output dependent on data, it is imperative that not only the arithmetic average of the output developed be brought within an acceptable range, but also as many other of the statistical properties as possible.

It was also demonstrated that, even in a simplified form, the mathematical model still produced profiles representative of natural conditions.

An aspect of the modeling procedure not receiving much attention, but which was shown to be of great importance, was that of the length of period being simulated. The effect of this parameter was revealed in the Partial Period Simulations of Section 4.4.2. Further, it may be concluded that, in order to develop a truly complete study of temperature effects, it will be necessary to subdivide the period being simulated so as to observe the effect of extreme low flows overlooked in this analysis. Of course, the frequency of such events must also be kept in view.

CHAPTER V
DATA COLLECTION

5.1 MONITORING SYSTEMS FOR THE COLLECTION OF TEMPERATURE DATA AND MAINTENANCE OF TEMPERATURE REGULATIONS

The ability to continuously monitor temperature (as well as other water quality parameters) has been shown to be a basic necessity to temperature studies and of utmost importance to a final analyses. In the following pages a guide will be organized which will aid in the planning and establishment of automatic, continuous temperature monitoring systems. It should be recognized that probably, parameters other than those directly related to temperature investigations will be measured depending upon the scope and goals of the study. Further it is assumed that automatic systems are preferable to manually operated systems. This preference has been established since the earlist surveys which were time consuming and required considerable man power. Such deficiencies have inspired the development of sophisticated electronic instrumentation for the measurement and record of water temperatures.

In initial study proposals it is supposed that the study area has been well defined, and therefore limits of the area to be surveyed are known. Recognizing budgetary limitations and having at hand current equipment and operational costs, simple computations will yield the approximate number of monitoring stations which may be placed over the study area. Hopefully this number equals or exceeds that deemed necessary to develop accurate temperature profiles.

The parameters most useful to a study are (1) water temperature at several depths, (2) dissolved oxygen, (3) air temperature, (4) wet and dry bulb temperatures or relative humidity, (5) wind speed and direction, and (6) solar radiation.

Instrumentation to implement a study and which meets specified requirements is now (1968) commercially available. Basically, the instrument package consists of 2 or 3 units or compartments. A lower chamber housing sensors, receives a continuous flow of water from submersible pumps. The electric pump (2 pumps if information is taken at two different depths) may be supported about one foot below the surface of the water by a float arrangement which rises and falls with changes in surface elevation, whether caused by tidal effects or changes in flow. The water sample travels through the parallel sampling chambers, then passes to an overflow. A middle section contains the analyzing equipment. The top section contains recording equipment.

One may question our ability to observe and analyze great amounts of data. This is, of course, no problem with the aid of high speed electronic computers. We can handle any amount of data that will be available. Recording information in the proper form when obtained can speed up the analyzing process greatly. When a monitoring system runs continuously day after day and large amounts of data are collected and it is most convenient to record the data digitally, as on punched paper tape or magnetic tape for later processing by a computer. Transcribing information from charts has been found to be so time consuming that economic justification of the additional equipment needed to shift this burden to a machine is readily made. With the addition of a digital clock, real time can be recorded. Station position may also be coded on the tape. Tape recordings of these types are a very convenient means of storing quantities of data which can be read and reproduced in any other form by computer methods.

The maintenance of the system can be quite simple. Periodically the main sampling chamber is disassembled, cleaned and flushed out. Most elements of the sampling tanks are designed to be resistant to marine fouling and for easy maintenance, making the entire cleaning process about a 15-minute job. Occasionally the submersible pump and piping system must be flushed. This may be accomplished, as described by Cory and Davis(34), by placing the pump in a 20 gallon container about half full of water. The water flows through the piping and is returned to the container. One cup of chlorine-base bleach is added to the water and solution circulated long enough to kill biota attached to the inside of the pipes.

The need for adjustment of calibration has been reduced greatly over equipment of earlier periods. Experience has shown that most all the sensing devices utilized need no adjustment if not subject to abuse or unusual environmental conditions. A report[25] of one automatic data system in operation supporting this states in one case:

> The extremely stable and accurate oxygen sensor has operated continuously for nearly a year with no adjustments of calibration, and no maintenance other than an occasional wiping of the membrane with a soft cloth. A jet stream of water directed against the sensing membrane prevents settling of fouling organisms.

A desirable trait of a monitoring station would be the ability of easy relocation. A movable monitoring unit would optimize the equipment investment. "Movability" is often necessary in view of the type of surveys carried out.

A complete survey of a river will incorporate a number of schemes for distribution of monitoring stations. Each scheme will have specific aims and purposes. First, a preliminary survey encompassing the entire river would be carried out. Such a survey would allow the immediate visualation of the pattern of temperature and any trends in the variation of temperature patterns. This survey would then be followed by a number of surveys of much smaller scope. This second type would facilitate examining more closely selected reaches of stream in order to determine what factors influence the different parameters and also to construct more accurate temperature profiles. The number of reaches to be examined would be a function of meteorologic and hydrologic variables. The goal is to choose the smallest number of reaches which exhibit, as well as possible, conditions over the entire river. Not only would points along the length of a reach be examined but also cross-sectional profiles would be taken. This refinement will enable viewing the extent of stratification and mixing which is taking place.

There are a number of precautions which must be observed when installing and using the instruments. To mention a few: (1) care must be exercised to see that the temperature registered is representative for the cross-section; (2) a site where incomplete mixing exists is unsuitable for the collection of water temperature data; and (3) temperature probes should not rest on the stream bed.

5.2 INSTRUMENTATION FOR DATA COLLECTION AND FOR SUPERVISION AND MAINTAINANCE OF TEMPERATURE REGULATIONS

It has been emphasized that there has been an acute neglect of water quality monitoring in most important streams. Inconsistent with this fact is the fact that within the past five years fine electronic monitoring equipment has become available.

Water quality monitoring systems capable of data acquisition, logging, transmission, display and conversion are commercially produced. Such equipment is found in a variety of configurations for automatic, continuous scanning of twenty or more physical and chemical parameters in shelter, trailer, or survey boat applications. Many feature solid-state electronics and modular, plug-in subassemblies for increased reliability and ease of maintainance.

Two basic equipment configurations yield wide overall flexibility, the single and multi-unit assemblies. The simplest type is made up of a single monitor probe with sensor chamber, electronics section and any form of logging or visual presentation. The second employs a modular design with the flexibility for incorporating a selection of visual, logging or telemetry components.

The modularized system is designed for permanent or semi-permanent installations which may operate continuously and unattended. The only other items needed to complete an installation are a submersible pump and piping to provide a constant flow of representative test water, a weatherproof shelter, and 120 V, 60 cps service. These modular systems can be readily disassembled for moving where short-term data collection is desired.

In some kinds of installations, particularly where short-term survey work is being done or where water must be pumped a considerable distance to the sensors, it is more convenient to use sensor assemblies that can be immersed directly into the water to be tested. Such systems have the advantage of maximum portability especially important in area survey work.

5.2.1 TEMPERATURE MEASUREMENT (water and air)

Two types of temperature sensing devices are commonly employed. They are the well-known thermocouple and thermister. The thermocouple is composed of two dissimilar metal wires buttwelded to form a sensing junction. The thermocouple develops a d-c millivolt out put proportional to the temperature difference between the sensing junction and reference junctions in the measuring instrument. The thermistor is a semi-conductor in which a slight change of temperature results in a pronounced change of electrical resistance. Accurate measurement of this change of resistance therefore reads the temperature at the thermistor position. Thermistors, historically, have demonstrated individual and differing temperature vs. resistance response curves. This severely limited broad usage, however new processes for producing thermistors of similar characteristics have been developed thereby facilitating interchangeability. Thermistors do tend to shift response slightly with time and thermal shock.

Most manufacturers offer several instruments for either displaying or recording temperatures as reported by the sensors previously described. Depending upon the type of survey being conducted one of these types may have better application. Direct dial indicators require hand recording of measurements, while automatic amplification, signal conditioner analog or digital systems find greater application.

5.2.2 RADIATION MEASUREMENTS

Several methods have been employed to measure solar and atmospheric radiation. One requires the separate measurement and recording of short and long wave radiation. Solar radiation is measured using an Eppley 180° pyrheliometer and total radiation by using a Gier and Dunkle flat-plate radiometer. (Dunkle et al, 1949)

Atmospheric radiation is then computed as the difference in the two measured quantities. The Cummings Radiation Integrator (Cummings, 1940) might also be used to measure total incoming radiation.

The heart of the Eppley pyrheliometer is an assembly of concentric silver rings with black and white surfaces. These surfaces are subjected to radiant energy and assume different temperatures. A thermopile in contact with the surfaces senses this temperature difference, and converts it to a d-c millivolt signal for a potentiometer recorder. The thermopile is made of fine gold palladium and platinum rhodium alloy wires. Basically a number of thermocouples in series, it produces a higher millivolt output than would be possible with an individual thermocouple. The pyrheliometer has a 10-junction thermopile which provides approximately a 2.5 millivolt output for a radiation intensity of 1 calorie per square centimer per minute. Approximately 1.5 calories per square centimeter per minute is usually accepted as representative of the maximum intensity of total sun and sky radiation received at any point on the earth's surface.

This assembly is mounted in a glass bulb which has been carefully heated, dried and filled with dry air. This prevents any condensation from forming when the unit is exposed to low temperatures.

The basic operating principle is the sensation of temperature difference between the two concentric ring surfaces. When solar radiation strikes the sensitive surfaces on the top of the rings, most of the energy striking the black surface is absorbed. The heat produced is sensed by the hot junctions of thermopile. Concurrently, most of the radiated energy striking the white surface is reflected away and comparatively little heat is produced. This provides the cold junction temperature for the thermopile. The d-c electrical signal produced by the thermopile is directly proportional to the intensity of the radiated energy rate.

The Gier-Dunkle flat-plate radiometer is made up of a flat plate of aluminum with a blackened upper surface and a polished lower surface and a thermopile in between the two surfaces to measure the temperature gradient. Mounted horizontally, the plate receives the discharge of an air blower across its upper surface. To determine the back radiation of the plate the upper surface temperature is measured by means of a thermocouple. The total radiation absorbed is proportional to the thermopile voltage after correction for back radiation.

The Cummings Radiation Integrator is an insulated pan of water whose heat budget may be utilized to compute total incoming radiation from measurements of air and water temperatures.

Either the pyrheliometer or flat-plate radiometer could be used in an inverted mounting position to facilitate the measurement of reflected radiation.

5.2.3 WIND SPEED AND DIRECTION

Commercially available instruments for measuring wind speed and direction follow very similar designs. Basically a propeller senses wind speed with the rate of tunning being proportional to the speed of the wind. Another method of obtaining wind speed employs the rotation of a generator, attached to a three-cup assembly by means of a shaft. The current produced by the generator is directly proportional to the rate of rotation of the cup assembly and wind speed. Wind direction is sensed by a potentiometer facilitating digital recording systems. Another design utilizes a variable resistor which is in contact with the rotating wind vane shaft. The voltage output from the variable resistor is a function of the vane's position.

More familiar to engineers are the means of measuring Relative Humidity, Precipitation and Pressure. An abbreviated description will therefore be given.

5.2.4 RELATIVE HUMIDITY

Automatic systems for obtaining a record of relative humidity utilize a long bundle of human hair which expands or contracts as humidity changes.

5.2.5 PRECIPITATION

Modern instruments facilitate automatic, accurate measurement of rain fall. Although simple the method of operation is sufficient for all uses. Basically, either a system of two buckets alternatively fill and tip causing closure of a switch or a weighing system is employed to activate a data acquisition system.

5.2.6 PRESSURE

Modern recording type barometric pressure measurement instruments employ, as in the past, an aneroid sensor. Such sensors are constructed of a special copper alloy and are so designed as to allow adjustment for operation at most any altitude.

Much work is needed on the method of data recording for these last three parameters. Analog systems have been most convenient and popular but do not facilitate easy handling or reduction of the data.

CHAPTER VI
DISCUSSION AND CONCLUSIONS

6.1 DISCUSSION

There was a threefold objective of this paper. The first was to identify and review significant research contributions, the second, to suggest a practical technique for approaching and solving thermal problems, and the third, to develop a mathematical model which would aid in the solution of these problems by simulating stream temperature. Also, throughout the paper are interjected many facts which are helpful to a thorough understanding of the immediate discussions. The information is sufficiently complete either as presented or in referenced form so the necessary tools for accomplishing a solution are at hand in one, more or less, condensed volume.

It is believed that the presentation and discussion of earlier research works dealing with the engineering aspects of thermal problems is the most complete to date. The detail in which many aspects of the problem are covered is not repeated for brevity, however, it is imperative that this detail be assimilated in order to support a deeper understanding of the problem.

A majority of the earlier studies have supported one of two approaches to the development of a simulation model, the heat or energy budget or the exponential or natural decay of excess temperature. The heat balance was the first conceived and had several inherently difficult features. These difficulties prompted the development of exponential decay theory. However, from the point of view of an analyst in need of a computational method, the exponential decay method does not yield much advantage. Beyond the difficult mathematic relationships which must be understood is the fact that there is still a large amount of basic data necessary to implement the model.

The results of this study, it is believed, contribute to the successful application of the heat budget method by supplying additional tools which aid in its solution. The tools which found greatest application included random number treatment of incoming radiation and computer techniques. Also new information regarding natural heating, in the form of nomographs constructed from many thousands of measurements of incident radiation have made it possible to apply the heat balance method with more ease. In addition, much more information which is useful in these studies is now being obtained routinely at weather stations and laboratories.

The nature of the investigation did not permit the study of a problem from its beginning, the necessary resources and time available being limited. To short-cut the expensive and time-consuming process of collecting data for a thermal study, a successful effort was made to obtain existing data which was sufficiently complete. The suggestions regarding the acquisition of data, therefore, could not be evaluated and likewise the guidelines which were set down in Section 2.4.1 were not relied upon until section H, "data reduction and storage". This and each succeeding section was expanded and more clearly defined upon its application.

One capability which can be built into the model which will be of special value regarding the establishment of a plan of development for a river basin is that of determining the optimium arrangement or combination of temperature control devices. As indicted previously, the requisite techniques to accomplish this end are available.

6.2 CONCLUSIONS

(1) The heat budget procedure for approaching and solving thermal problems as outlined here is sound and practical as shown in part through the solution of the case study.

(2) The mathematical model is, in its present form, capable of predicting useful information regarding the temperature regime which would exist under both natural and artifically heated conditions.

(3) The results must be viewed as conservative in light of the assumptions upon which they are based.

(4) More valuable information will be yielded upon an examination of several of the assumptions. These include assumptions regarding: (a) outlet mixing conditions, (b) the distribution of maximum incident radiant energy which may strike a water surface, (c) geographic effects on the adjustment of data from distant collection stations, and (d) the surface

area over which transfer of energy is effectively taking place.

(5) The effect of run-of-the-river impoundments can be included in the model.

6.3 SUGGESTIONS FOR FURTHER RESEARCH

Several areas worthy of additional study regarding the modelling techniques can be suggested. As was mentioned while the subject was being developed, the distribution resulting from the randomly selected values of radiation could take any form. As a uniform distribution was used, the question arose whether or not another distribution would be more realistic, this would have to be investigated. This is a topic which falls into the discipline of meteorology or climatology. The results of such an investigation would be a valuable contribution to the overall development of this prediction technique.

Another area which must receive attention before the modelling technique can be fully verified is that concerning the extent of mixing which takes place at the discharge. For simplicity it was assumed, as it has very often been in the past, that complete mixing took place while experience has shown that, in fact, it is likely that stratified flow may result and consequently losses to the atmosphere are greatly in error. The results of the model studies are consistent with these thoughts in the following ways. First the model results indicated that the distance required to return stream temperatures to natural levels was quite large in relation to what might be expected based on experience. This is because the surface temperatures resulting under assumed mixed conditions are considerably lower than for stratified conditions and subsequently the losses to the atmosphere are proportionately lower. Had a stratified condition been assumed to exist, heat loss rates would have been much higher and the average temperature of the flow at downstream sections would have been lower. Certainly, these conditions must be studied. To accomplish this the strength of forces tending to establish stratified conditions must be evaluated by investigating the Densimetric Froude number. It has been found in studies by Bata[35] that when $F < 1.0$ stratified conditions will exist. Such determinations when carried out simultaneously with heat balance computations will yield more realistic temperature profiles.

REFERENCES

1. Leberge, Ronald H., "Thermal Discharge" Water and Sewage Works, Dec. 1959

2. Moore, E. W. "Thermal Pollution of Steams," Industrial and Engineering Chemistry, Vol. 50, No. 4, Apr. 1958 pp. 87A & 88A

3. Hoak, Richard D., "Defining Thermal Pollution," Power Engineering, Dec. 1961

4. Cootner, P. H., and B. O. G. Lof, "Water Demands for Steam Electric Generation,"Resources for the Future, Inc. 1965, Washington, D. C.

5. Lima, D. O., "Pond Cooling by Surface Evaporation" Power Vol. 80, No. 3, 1936, pp. 142-144

6. Lamb, N., "Power Station Cooling Ponds" Projects Division, Power Development Branch, The Electricty Commission of New South Wales, Australia

7. Thorne, R. F., "How to Predict Lake Cooling Action" Power, Vol. 95, Sept. 1951, p. 86

8. Cotter, T. J. and Lotz, A. W. "Cooling Pond Design in the Southwest", Journal of the Power Division, A.S.C.E., Paper No. 2861, July 1961

9. Edinger, J. E. and Geyer, J. C., "Heat Exchange in the Environment," EEI Publication No. 65-902, Edison Electric Institute, June 1965

10. Richards, R. T., "Water Resources Planning-Its Influence on Thermal Station Design", Presented A.S.C.E. Conference, New York, N.Y., Oct. 1967

11. Goitein, E. E., "Selection and Application of Cooling Towers", Presented at Power Division Conference A. S. C. E., Allentown, Penna., Oct. 21-23, 1957

12. Converse, A. D., "Thermal Energy Disposal Methods for The Proposed Nuclear Power Plant at Vernon Vermont" Submitted as a Public Service to the State of Vermont Thayer School of Engineering, Darthmouth College, Nov. 17, 1967

13. Gausmann, R. W., "Cooling Towers Gain Acceptance", Electrical World News, Ed. No. 144, pp. 16-18 July, 1955

14. Jaske, R. T., Goebel, J. B., "Effects of Dam Construction on Temperatures of the Columbia Rivers", J.A.W.W.A. Vol. 59, No. 8, Aug. 1967

15. Churchiss, M. A., "Control of Temperature Through Steam Flow Regulation", U.S. Dept. HEW, Public Health Series Publication No. 999-WP-30, p. 179

16. Mihursky, J. A., "On Possible Constructure Uses of Thermal Additions to Estuaries, "BioScience, Vol 17, No. 10, 1967, pp. 698-702

17. Odum, H. T., "Energy Transfer and the Marine Systems of Texas," Presented at the Conference on Pollution and Marine Ecology, Mar. 24-26, 1966 Galveston, Texas

18. LeBosquet, M. "Cooling Water Benefits from Increased River Flows", Journal, New England Water Works Association Vol. 60, No. 2, June 1946, p. 11

19. Harbeck, G. E. Jr. and Kennon, F. W. "The Water Budget Control", Lake Hefner Studies, Circular No. 229, Geological Survey, U.S. Dept. of the Interior, 1952

20. Harbeck, G. E. Jr., Kohler, Max A., Koberg, Gordon E., et. al., "Water-Loss Investigations, Lake Mead Studies", Professional Paper No. 298, Geological Survey, U.S. Dept. of the Interior, 1958

21. Gameson, A. L. H., Hall, H., and Preddy, W. S. "Effects of Heated Discharges on the Temperature of the Thames Estuary", The Engineer, Dec. 6, 13, 20, 1957

22. Velz, C. J., and Gannon, J. J. "Forecasting Heat Loss in Ponds and Streams", Journal, Water Pollution Control Federation, 32(1960)pp. 342-417

23. Raphael, J. M., "Prediction of Temperature in Rivers and Reservoirs", Proceedings A.S.C.E., 88: PO2: pp. 157-181 (Separate No. 3200)

24. "Heat Dissipation in Flowing Streams", Report of the 1960-61 Advanced Seminar, Dept. of Sanitary Engineering and Water Resources, Johns-Hopkins University, Baltimore, Md. Dec. 1961

25. Duttweiler, D. W. "A Mathematical Model of Stream Temperature", The Johns-Hopkins University, Baltimore, Md. 1963

26. Edinger, J.E. and Geyer, J.C., "Heat Exchange in the Environment", EEI Publication No. 65-902, June 1965

27. Pritchard, D. W., and Carter, H.H. "On the Prediction of the Distribution of Excess Temperature From A Heated Discharge in an Estuary", Johns-Hopkins University, Chesapeake Bay Institute, Feb. 1965

28. Reid, G.K., "Ecology of Inland Waters and Estuaries", Reinhold Pub. Corp., New York, 1961

29. "Interior Report of the National Technical Advisory Committee of the F. W. P. C. A. on Water Quality Criteria" U.S. Dept. of Interior, June 30, 1967, Washington D.C.

30. "Water and Power in the Connecticut River Basin", Ebasco Services, Inc. 2 Reactor St. N.Y., N.Y., May 1966

31. Bowen, I.S. "The Ratio of Heat Losses by Conduction and by Evaporation from Any Water Surface", Physical Review, Vol. 27, No. 2, June 1926, pp. 779-787

32. "An Introduction to Linear Programming", IBM, 1964

33. Harmon, W.R., et. al., "Insolation as an Empirical Function of Daily Sunshine Duration", Monthly Weather Review, Vol. 82, No. 6, 1954, p. 141

34. Cory, R. L. and Davis, H.F., "Automatic Data System Aids Thermal Pollution Study of Patuxent River", Water and Sewage Works, April 1965

35. Bata, Geza L., "Recirculation of Cooling Waters in Rivers and Canals", Journal of the Hydraulic Division, A.S.C.E., Vol. 83, No. HY3, Proc. Paper 1265, June 1957

APPENDIX A

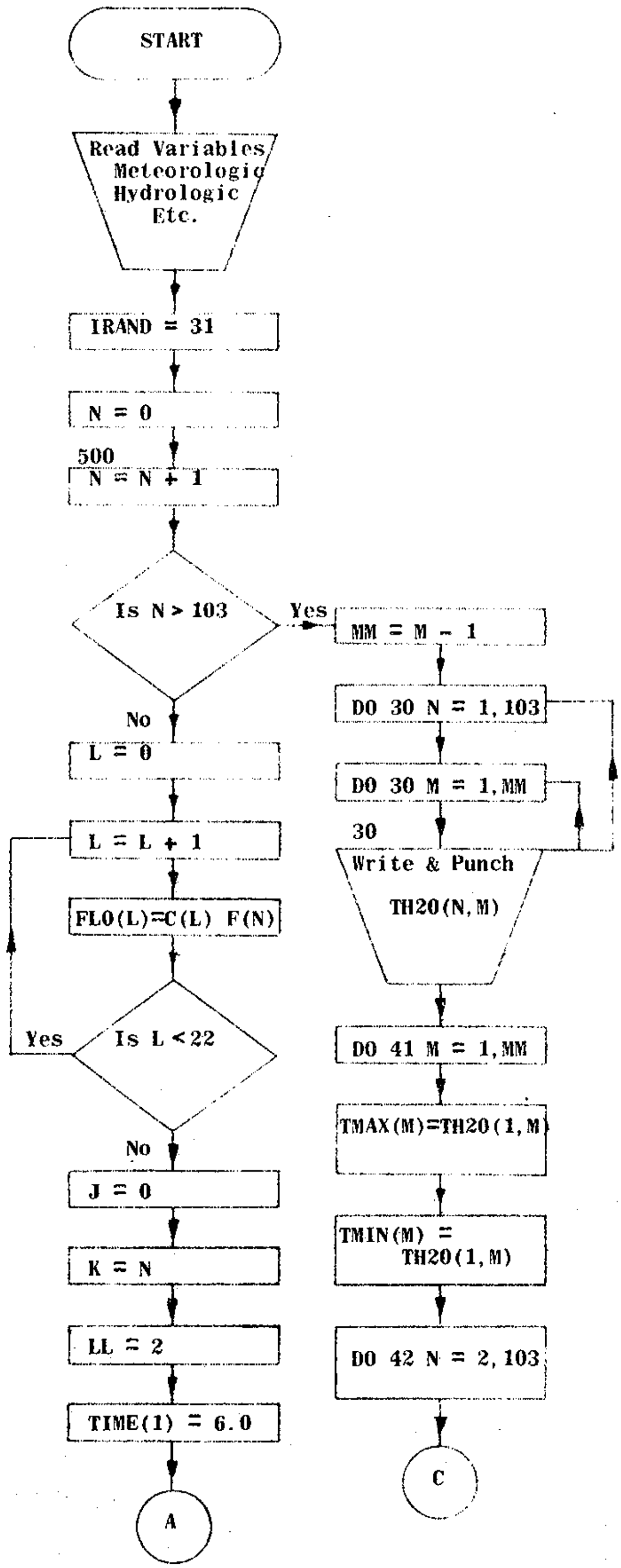
GLOSSARY OF SYMBOLS

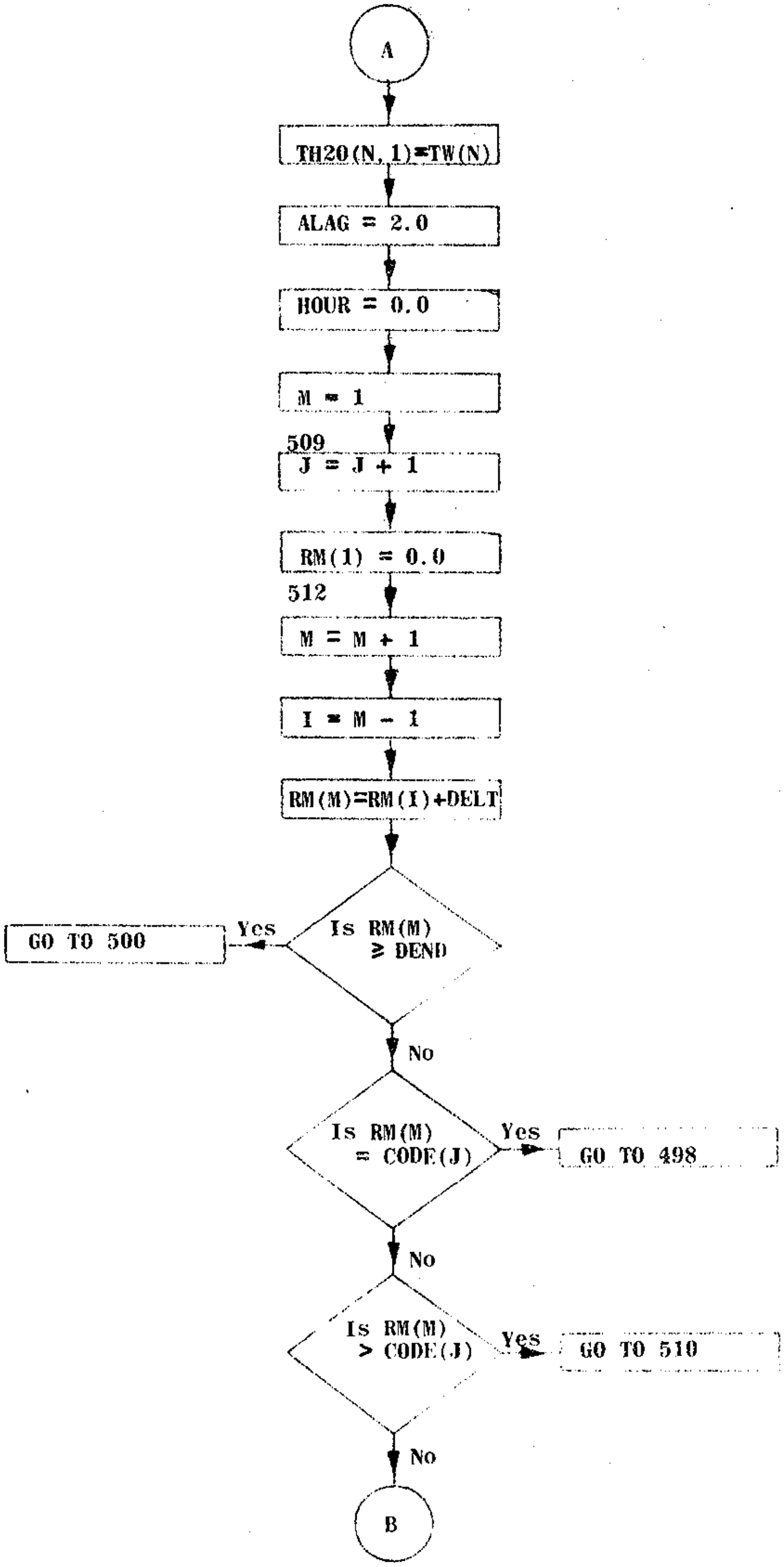
SYMBOL	DESCRIPTION	TYPICAL UNITS
A	Area; cross-sectional area	sq. ft.
A	Vertical component of eddy conductivity	dimensionless
A_1	Area of cooling pond	acres
a	Empirical parameter	BTU/(sq. ft.)(hr.)
b	Empirical parameter	BTU/(sq. ft.)(hr.)
C_p	Specific heat at constant pressure	BTU/(lb)(degrees F)
c	Empirical parameter	BTU/(sq. ft.)(hr.)
d	Empirical parameter	BTU/(sq. ft.)(hr.)
d_1	Mean depth of cooling pond	feet
e_a	Vapor pressure of air	mm Hg.
e_s	Saturation vapor pressure at water surface temperature	mm Hg.
F	Froude number	dimensionless
HI	Total heat input to a reach in time, t.	B.T.U.
K	Heat exchange coefficient	BTU/(sq. ft.)(hr.)
m	Fraction of mean pond depth occupied by outflow from a plant	degrees F
Patm.	Atmospheric pressure	millibars
Q	Heat absorbed or dissipated per unit area	BTU/ (sq. ft.)
Q_a	Atmospheric long wave radiation from a clear sky (incoming energy)	BTU/(hr.)(sq. ft.)
Q_{ac}	Atmospheric long wave radiation from an overcast sky (incoming energy)	BTU/(hr.)(sq. ft.)
Q_{ad}	Heat energy advected from water surface (outgoing energy)	BTU/(hr.)(sq. ft.)
Q_{ar}	Atmospheric long wave radiation reflected from water surface (outgoing energy)	BTU/(hr.)(sq. ft.)

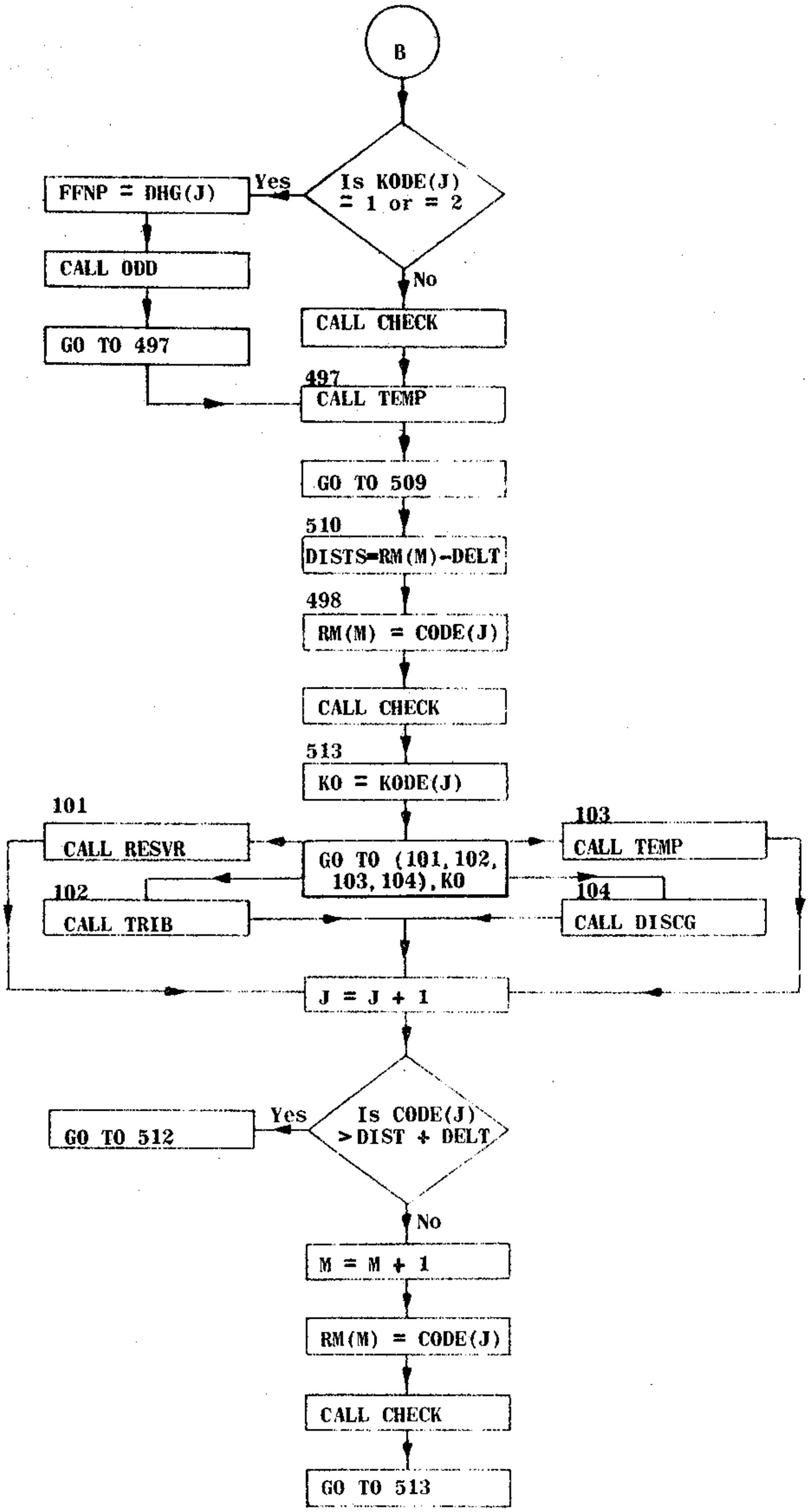
SYMBOL	DESCRIPTION	TYPICAL UNITS
Q_{br}	Long wave radiation from water surface (outgoing energy)	BTU/(hr.)(sq. ft.)
Q_c	Heat energy conducted from water surface as sensible heat (out-going energy)	BTU/(hr.)(sq. ft.)
Q_e	Heat energy utilized in evaporation (outgoing energy)	BTU/(hr.)(sq. ft.)
Q_f	The average flow rate through a reach	cfs
Q_h	Net heat input rate	BTU/(sq. ft.)(hr.)
Q_{hd}	Heating rate from artificial sources	BTU/(sq. ft.)(hr.)
Q_{nr}	Net natural heat energy rate	BTU/(sq. ft.)(hr.)
Q_p	Plant discharge rate	cfs
Q_s	Solar short wave radiation incident on water surface (incoming energy)	BTU/(sq. ft.)(hr.)
Q_{sr}	Solar short wave radiation reflected from water surface (outgoing energy)	BTU/(sq. ft.)(hr.)
R	Bowen ratio	dimensionless
T	Plant discharge temperature	degrees F.
T_a	Absolute temperature	degrees F.
T_a	Air temperature	degrees F.
T_b	Arbitrary base temperature	degrees F.
T_e	Temperature at which evaporation takes place	degrees F.
T_o	Equilibrium temperature	degrees F.
T_s	Water surface temperature	degrees F.
ΔT	Temperature change through reach	degrees F.
t	Travel time	hrs.
t_e	Time available for cooling in a flow through pond	hrs.
t'_e	Time available for cooling in an internally circulating pond	hrs.
V_1	Mean volume of cooling pond	ac. ft.

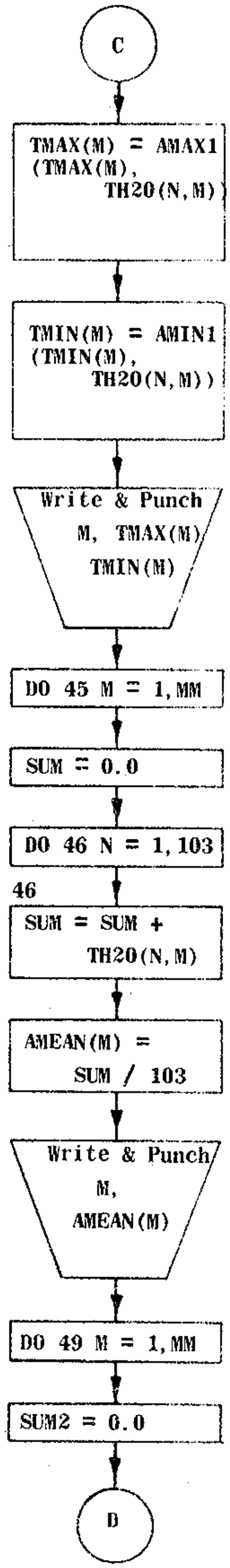
SYMBOL	DESCRIPTION	TYPICAL UNITS
V_e	Volume of evaporated water	ac. ft.
V	Velocity	ft. /sec.
W	Wind speed	miles/hr.
W_i	Wind speed at elevation i	miles/hr.
w	Width of stream	ft.
γ	Adiabatic lapse rate	dimensionless
λ	Empirical coefficient which is a function of cloud height	dimensionless
λ	Latent heat of vaporization of evaporated water	BTU/lb.
ρ	Unit weight of water	lbs/ft^3
ρ_e	Unit weight of evaporated water	lbs/ft^3
σ	Stefan-Boltzmann constant	dimensionless
τ	Travel time	seconds

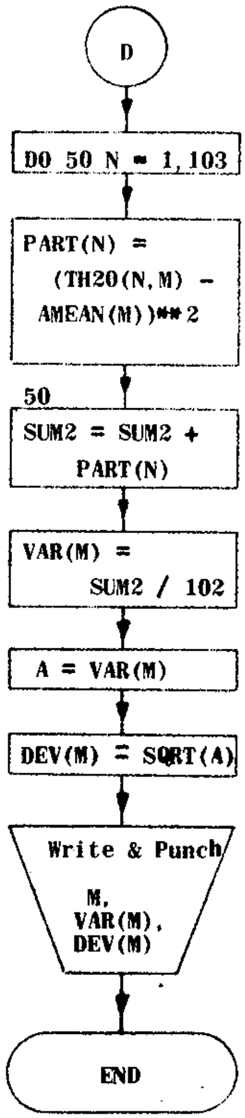
APPENDIX B


START
Read Variables
Meteorologic
Hydrologic
Etc.
IRAND = 31
N = 0
500
N = N + 1
Is N > 103
Yes
No
L = 0
L = L + 1
FLO(L)=C(L) F(N)
Is L < 22
Yes
No
J = 0
K = N
LL = 2
TIME(1) = 6.0
A
MM = M - 1
DO 30 N = 1, 103
DO 30 M = 1, MM
30
Write & Punch
TH20(N, M)
DO 41 M = 1, MM
TMAX(M)=TH20(1, M)
TMIN(M) =
TH20(1, M)
DO 42 N = 2, 103
C


A
TH20(N,1)=TW(N)
ALAG = 2.0
HOUR = 0.0
M = 1
509
J = J + 1
RM(1) = 0.0
512
M = M + 1
I = M - 1
RM(M)=RM(I)+DELT
Is RM(M) ≥ DEND
Yes
GO TO 500
No
Is RM(M) = CODE(J)
Yes
GO TO 498
No
Is RM(M) > CODE(J)
Yes
GO TO 510
No
B


B
Is KODE(J) = 1 or = 2
Yes
FFNP = DHG(J)
CALL ODD
GO TO 497
No
CALL CHECK
497
CALL TEMP
GO TO 509
510
DISTS=RM(M)-DELT
498
RM(M) = CODE(J)
CALL CHECK
513
KO = KODE(J)
101
CALL RESVR
GO TO (101,102, 103,104),KO
103
CALL TEMP
102
CALL TRIB
104
CALL DISCG
J = J + 1
Is CODE(J) >DIST + DELT
Yes
GO TO 512
No
M = M + 1
RM(M) = CODE(J)
CALL CHECK
GO TO 513


C
TMAX(M) = AMAX1 (TMAX(M), TH20(N,M))
TMIN(M) = AMIN1 (TMIN(M), TH20(N,M))
Write & Punch M, TMAX(M) TMIN(M)
DO 45 M = 1,MM
SUM = 0.0
DO 46 N = 1,103
46
SUM = SUM + TH20(N,M)
AMEAN(M) = SUM / 103
Write & Punch M, AMEAN(M)
DO 49 M = 1,MM
SUM2 = 0.0
D


D
DO 50 N = 1, 103
PART(N) = (TH20(N,M) - AMEAN(M))**2
50
SUM2 = SUM2 + PART(N)
VAR(M) = SUM2 / 102
A = VAR(M)
DEV(M) = SQRT(A)
Write & Punch
M, VAR(M), DEV(M)
END

```
C     ***********************************************************
C     *********************  WHITE RIVER MODEL  ***************
C     ***********************************************************
      DIMENSION CPTW(103),CPTA(103,21),QR(103,11),XWIND(103),
     1          COEFF(21),FLOW(103),RISE(103),SET(103),
     2          QNR(20),QBR(20),TH2O(103,21),QE(20),QC(20),
     3          WET(103,3),DRY(103,3),TIME(100),A(103),B(103),
     4          TMAX(21),TMIN(21),AMEAN(21),PART(103),VAR(21),
     5          CPFLO(21),VEL(100),CPVEL(21),FLO(100),TA(100),
     6          CODE(100),KODE(100),VOL(103,20),DETT(103,20),
     7          RELSE(103,20),DWITH(103,20),INFLO(103,20),
     8          DHG(103,30),TDHG(103,30),INCRS(103,20) ,DEV(21),
     9          SUNUP(103),CPRM(21),RM(100),QH(20),C(103),
     0          QP(103,10),TPDHG(103,10)
      WRITE(6,502)
  502 FORMAT(1H1,10X,29HTEMPERATURE PROFILE DEVELOPER//)
      READ (5,1) (CPTW(N),N=1,103)
      WRITE(6,4) (CPTW(N),N=1,103)
      DO 200 N=1,103
      READ (5,2)(CPTA(N,M),M=1,21)
  200 WRITE(6,2)(CPTA(N,M),M=1,21)
      READ (5,5)(XWIND(N),N=1,103)
      WRITE(6,5)(XWIND(N),N=1,103)
      DO 350 N=1,103
      READ (5,17) (DRY(N,J),WET(N,J),J=1,3)
  350 WRITE(6,17) (DRY(N,J),WET(N,J),J=1,3)
      DO 300 N=1,103
      READ (5,3)(QR(N,J),J=1,11)
  300 WRITE(6,3)(QR(N,J),J=1,11)
      READ (5,5)(FLOW(N),N=1,103)
      WRITE(6,5)(FLOW(N),N=1,103)
      READ (5,15) (COEFF(N),N=1,21)
      WRITE(6,15) (COEFF(N),N=1,21)
      READ (5,9)(CPRM(M),M=1,21)
      WRITE(6,9)(CPRM(M),M=1,21)
    1 FORMAT (67X,F3.0)
    2 FORMAT ( 7X,21F3.0)
    3 FORMAT (6X,11F6.0)
    4 FORMAT(20(1X,F3.0))
    5 FORMAT(8X,F4.0,11X,F4.0,11X,F4.0,11X,F4.0,11X,F4.0)
    8 FORMAT(6X,F4.0,F5.0,7X,F4.0,F5.0,7X,F4.0,F5.0,7X,F4.0,
     1 F5.0,7X,F4.0,F5.0)
    9 FORMAT(6X,13F5.1)
   10 FORMAT(16F5.3)
   15 FORMAT (11(1X,F6.4))
   17 FORMAT (19X,6F6.1)
      KJ=0
   24 KJ=KJ+1
      READ (5,18) CODE(KJ),KODE(KJ)
      KODEKJ=KODE(KJ)
      GO TO (25,26,27,28),KODEKJ
   25 DO 31 N=1,103
      READ (5,19) VOL( N,KJ),INFLO(N,KJ),RELSE(N,KJ),
     1  DETT(N,KJ),DWITH(N,KJ),IEOD
```

```
   31 CONTINUF
      GO TO 29
   26 DO 32 N=1,103
      READ (5,20) DHG(N,KJ),TDHG(N,KJ),IEOD
   32 CONTINUE
      GO TO 29
   27 READ(5,22) IEOD
      GO TO 29
   28 READ (5,20)QP(N,KJ)(INCRS(N,KJ),IEOD
   29 IF(IEOD.EQ.0) GO TO 24
      READ (5,21) DELTA
      DEND=CPRM(21)
   18 FORMAT (F6.2,2X,I1)
   19 FORMAT (4F15.0,19X,I1)
   20 FORMAT (2F15.0,49X,I1)
   21 FORMAT (F5.1)
   22 FORMAT(79X,I1)
      IRAND=31
C  START OF SIMULATION, TIME=0.0, CLOCK=12 MIDNIGHT OR 00.00
C   HOURS. WILL YIELD DATA FOR 103 CURVES - ONE FOR EACH DAY OF
C   THE STUDY PERIOD , MAY 10 THRU SEPT. 30, )965
      N=0
  500 N=N+1
      IF(N.GT.103) GO TO 505
      L=0
  501 L=L+1
      CPFLO(L)=COEFF(L)*FLOW(N)
      IF(L.LT.22) GO TO 501
      J=0
      K=N
      LL=1
      TIME(1)=6.0
      TH2O(N,1)=CPTW(N)
      ALAG=2.0
      HOUR=0.0
      M=1
  509 J=J+1
      RM(1)=0.0
  512 M=M+1
      I=M-1
      RM(M)=RM(I)+DELTA
      IF(RM(M).GT.DEND) GO TO 500
      IF(RM(M).FQ.CODE(J)) GO TO 498
      IF(RM(M).GT.CODE(J)) GO TO 510
      IF(KODE(J).EQ.1.OR.KODE(J).EQ.2) GO TO 499
      CALL CHECK
      CALL TEMP
      GO TO 509
  499 CALL XFLO
      CALL TEMP
      GO TO 509
  510 DISTS=RM(M)-DELTA
  498 RM(M)=CODE(J)
      CALL CHECK
```

```
513 KO=KODF(J)
    GO TO (101,102,103,104) , KO
101 CALL RESVR
    GO TO 511
102 CALL TRIB
    GO TO 511
103 CALL TEMP
    GO TO 511
104 CALL DISCG
511 J=J+1
    IF(CODE(J).GT.DISTS+DELTA) GO TO 512
    M=M+1
    I=M-1
    RM(M)=CODE(J)
    CALL CHECK
    GO TO 513
505 MM=M-1
    DO 30 N=1,103
    DO 30 M=1,MM
    WRITE(6,13) TH2O(N,M)
 13 FORMAT (11X,21F3.0)
 30 PUNCH 13, TH2O(N,M)
    WRITE (6,40)
 40 FORMAT (5X,1HM,3X,7HTMAX(M),1X,7HTMIN(M))
    DO 41 M=1,MM
    TMAX(M)=TH2O(1,M)
    TMIN(M)=TH2O(1,M)
    DO 42 N=2,103
    TMAX(M)=AMAX1(TMAX(M),TH2O(N,M))
 42 TMIN(M)=AMIN1(TMIN(M),TH2O(N,M))
    WRITE (6,43) M,TMAX(M),TMIN(M)
 41 PUNCH 43,M,TMAX(M),TMIN(M)
 43 FORMAT (4X,I2,2F7.0)
    WRITE (6,44)
 44 FORMAT (5X,1HM,1X,8HMEAN(M))
    DO 45 M=1,MM
    SUM=0.0
    DO 46 N=1,103
 46 SUM=SUM+TH2O(N,M)
    AMEAN(M)=SUM/103.
    WRITE (6,47) M,AMEAN(M)
 45 PUNCH 47, M, AMEAN(M)
 47 FORMAT (4X,I2,2X,F3.0)
    WRITE (6,48)
 48 FORMAT (5X,1HM,1X,6HVAR(M),1X,6HDEV(M))
    DO 49 M=1,MM
    SUM2=0.0
    DO 50 N=1,103
    PART(N)=(TH2O(N,M)-AMEAN(M))**2
 50 SUM2=SUM2+PART(N)
    VAR(M)=SUM2/102.
    A=VAR(M)
    DEV(M)=SQRT(A)
    WRITE (6,51) M,VAR(M),DEV(M)
```

```
   49 PUNCH 51 , M,VAR(M),DEV(M)
   51 FORMAT (4X,I2,F6.2,F7.2)
  999 CALL EXIT
      GO TO 999
      END
$IBFTC DXFLO
      SUBROUTINE XFLO
      COMMON DHG,KODE,INFLO,VEL,RM,CODE,TA,CPRM,CPTA,FLO,J,I,
     1  M,LL
      IF(KODE(J).EQ.1)FLUX=INFLO(J)
      IF(KODE(J).EQ.2)FLUX=DHG(J)
      FLO(1)=COEFF(1)*FLOW(N)
      VNP=0.036*((FLUX+FLO(I))**.541)
      VEL(1)=0.036*(CPFLO(1)**.541)
      VEL(M)=VEL(I)+(((RM(M)-RM(I))/(CODE(J)-RM(I)))*
     1    (VNP-VEL(I)))
      KL=22-LL
      TA(1)=CPTA(N,1)
      TA(M)=TA(I)+(((RM(M)-RM(I))/(CPRM(LL)-RM(I)))*
     1    (CPTA(N,KL)-TA(I)))
      FLO(M)=FLO(I)+(((RM(M)-RM(I))/(CODE(J)-RM(I)))*
     1  (FLUX-FLO(I)))
      RETURN
      END
$IBFTC DCHECK
      SUBROUTINE CHECK
      COMMON RM,CPRM,M,LL,FLO,CPFLO,VEL,TA,CPTA,CPVEL,I
      IF(RM(M).EQ.CPRM(LL)) GO TO 801
      IF(RM(M).GT.CPRM(LL)) GO TO 802
      IF(RM(M).LT.CPRM(LL)) GO TO 803
  801 CALL PROP1
      GO TO 804
  802 LL=LL+1
      CALL PROP2
  803 CALL PROP2
  804 RETURN
      END
$IBFTC DPROP1
      SUBROUTINE PROP1
      COMMON FLO,CPFLO,VEL,TA,CPTA,M,LL
      FLO(M)=CPFLO(LL)
      VEL(M)=0.036*(FLO(M)**.541)
      KL=22-LL
      TA(M)=CPTA(N,KL)
      RETURN
      END
$IBFTC DPROP2
      SUBROUTINE PROP2
      COMMON CPVEL,CPFLO,VEL,RM,CPRM,TA,CPTA,FLO,LL,M,I,FLOW
      CPVEL(LL)=0.036*(CPFLO(LL)**.541)
      VEL(1)=0.036*(CPFLO(1)**.541)
      VEL(M)=VEL(I)+(((RM(M)-RM(I))/(CPRM(LL)-RM(I)))*
     1          (CPVEL(LL)-VEL(I)))
      KL=22-LL
```

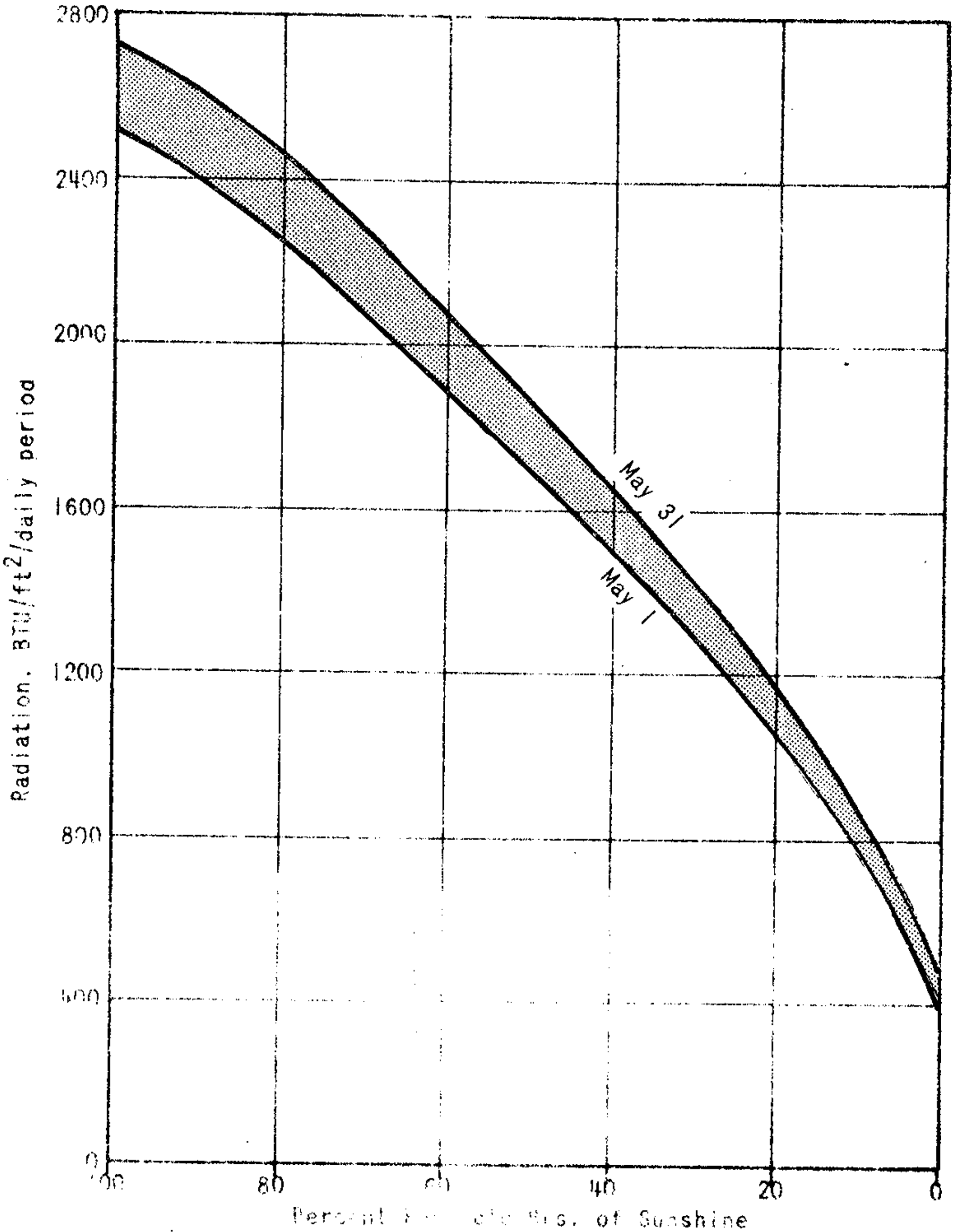
```
      TA(1)=CPTA(N,1)
      TA(M)=TA(I)+(((RM(M)-RM(I))/(CPRM(LL)-RM(I)))*
     1  (CPTA(N,KL)-TA(I)))
      FLO(1)=COEFF(1)*FLOW(N)
      FLO(M)=FLO(I)+(((RM(M)-RM(I))/(CPRM(LL)-RM(I)))*
     1          (CPFLO(LL)-FLO(I)))
      RETURN
      END
$IBFTC DTEMP
      SUBROUTINE TEMP
      COMMON RM,VEL,TIME,ALAG,J,TA,TH2O,DRY,WET,XWIND,DEND,
     1   FLO,N,M,I,K
     1   FLOW
      ADVAN=RM(M)-RM(I)
      FLO1=COEFF(I)*FLOW(N)
      FLO2=COEFF(M)*FLOW(N)
      VEL(I)=0.036*(FLO1**.541)
      VEL(M)=0.036*(FLO2**.541)
      PLUS =ADVAN/((VEL(M)+VEL(I))/2.)
      TIME(1)=6.0
      TIME(M)=TIME(I)+PLUS
      ARGUI=((TIME(I)-ALAG)*6.282)/24.
      ARGUM=((TIME(M)-ALAG)*6.282)/24.
      TRIGI=SIN(ARGUI)
      TRIGM=SIN(ARGUM)
      IF((ARGUM-ARGUI).GE.6.282) GO TO 101
      GO TO 102
  101 RATIO=1.0
      K=K+1
      AN=AN+1.0
      GO TO 103
  102 IF(AN.LT.31.)D=-(.165+(.135/31.)*AN)
      IF(AN.GE.31.)D=-(.435-(.435/97.)*AN)
      PIE=3.141
      PIEI=PIE/2.-D
      PIEM=3.*PIE/2.+D
      AUCT=2.-2.*D
      AUCI=-(TRIGI+D*ARGUI)
      AUCM=-(TRIGM+D*ARGUM)
      AUCPI=-(SIN(PIEI)+D*PIEI)
      AUCPM=AUCT+AUCPI
   57 IF(ARGUI.GT.6.282) GO TO 55
   58 IF(ARGUM.GT.6.282) GO TO 59
      GO TO 56
   55 ARGUI=ARGUI-6.282
      GO TO 57
   59 ARGUM=ARGUM-6.282
      GO TO 58
   56 IF(ARGUI.GT.ARGUM)ARGUM=ARGUM+6.282
      IF(ARGUI.LT.PIEI.AND.ARGUM.LE.PIEI)XNUM=0.0
      IF(ARGUI.LT.PIEI.AND.ARGUM.GT.PIEI)XNUM=AUCM+AUCPI
      IF(ARGUM.LT.PIEM.AND.ARGUI.GT.PIEI)XNUM=AUCM-AUCI
      IF(ARGUM.GE.PIEM.AND.ARGUI.LT.PIEM)XNUM=AUCPM-AUCI
      IF(ARGUI.GE.PIEM.AND.ARGUM.GT.PIEM)XNUM=0.0
```

```
      IF(XNUM.GT.AUCT.OR.XNUM.LT. 0.)XNUM=AUCT
      AXIS=PIFM-PIFI
      IF(ARGUI.LT.PIEI.AND.ARGUM.GT.PIEI)EXPOSE=(ARGUM-PIEI)/
     1   AXIS
      IF(ARGUM.LT.PIEM.AND.ARGUI.GT.PIEI)EXPOSE=(ARGUM-ARGUI)/
     1   AXIS
      IF(ARGUM.GE.PIEM.AND.ARGUI.LT.PIEM)EXPOSE=(PIEM-ARGUI)/
     1   AXIS
      RATIO=(XNUM/AUCT)*EXPOSE
      AN=AN+1.0
  103 IRAND=IRAND*41+3
      MOD=IRAND-((IRAND/100)*100)
      J=((MOD+1)/10)+1
      JJJ=11-J
      SHADE=0.1+(0.4/51.7)*(RM(I)+RM(M))/2.0
      QNR(I)=QR(K,J)*RATIO*SHADE
      KL=22-I
      L=21-I
      TAIR=(TA(N,KL)+TA(N,L))/2.
      IF(XNUM.EQ.0.) TAIR=TAIR-10.0
      SUB1=(TH2O(N,I)+460.)**4
      SUB2=(TAIR    +460.)**4
      QBR(I)  =.0000000349*(SUB1-SUB2)
      IF(QBR(I).LT.0.) QBR(I)=0.
      DBLB=(DRY(N,1)+DRY(N,2)+DRY(N,3))/3.
      WBLB=(WET(N,1)+WET(N,2)+WET(N,3))/3.
      DIFF=DBLB-WBLB
      IF(DBLB.LE.54.0) RH=100.-(6.06*DIFF)
      IF(DBLB.LE.63.0) RH=100.-(5.21*DIFF)
      IF(DBLB.LE.72.0) RH=100.-(4.56*DIFF)
      IF(DBLB.LE.81.0) RH=100.-(4.16*DIFF)
      IF(DBLB.LE.90.0) RH=100.-(3.71*DIFF)
      IF(DBLB.LE.99.0) RH=100.-(3.37*DIFF)
      EW=10.133-(4166.132/(TH2O(N,I)+460.))
      EA=RH/100.*(10.133-(4166.132/(TAIR+460.)))
      WIND=XWIND(N)/24.
      QE(I)   =0.57*WIND    *(EW-EA)
      QC(I)=0.138*WIND*(TAIR-TH2O(N,I))
      QH(I)=QNR(I)-QBR(I)-QE(I)+QC(I)
      W=250.
      RUN=(FLO1+FLO2)/2.
      WIDTH=((ADVAN/2.+RM(I))/RM(21))*W
C     HIWTR = HIGH WATER FLOW RATE UPON WHICH MAX. SURFACE AREA
C     IS BASED
C     THIS IS A TRIAL RUN FOR HIWTR = 1172.
C     STREAM SURFACE AREA ASSUMED A TRIANGULAR WEDGE TO
C     SIMPLIFY COMPUTATIONS
      HIWTR=1172.
      REDUCE = RUN/(((COEFF(I)+COEFF(M))/2.)*HIWTR)
      AREA=ADVAN*WIDTH*REDUCE*5280.
      HI=QH(I)*AREA
      WM=RUN    *224640.
      DELT    =HI/WM
      TH2O(N,M)=TH2O(N,I)+DELT
```

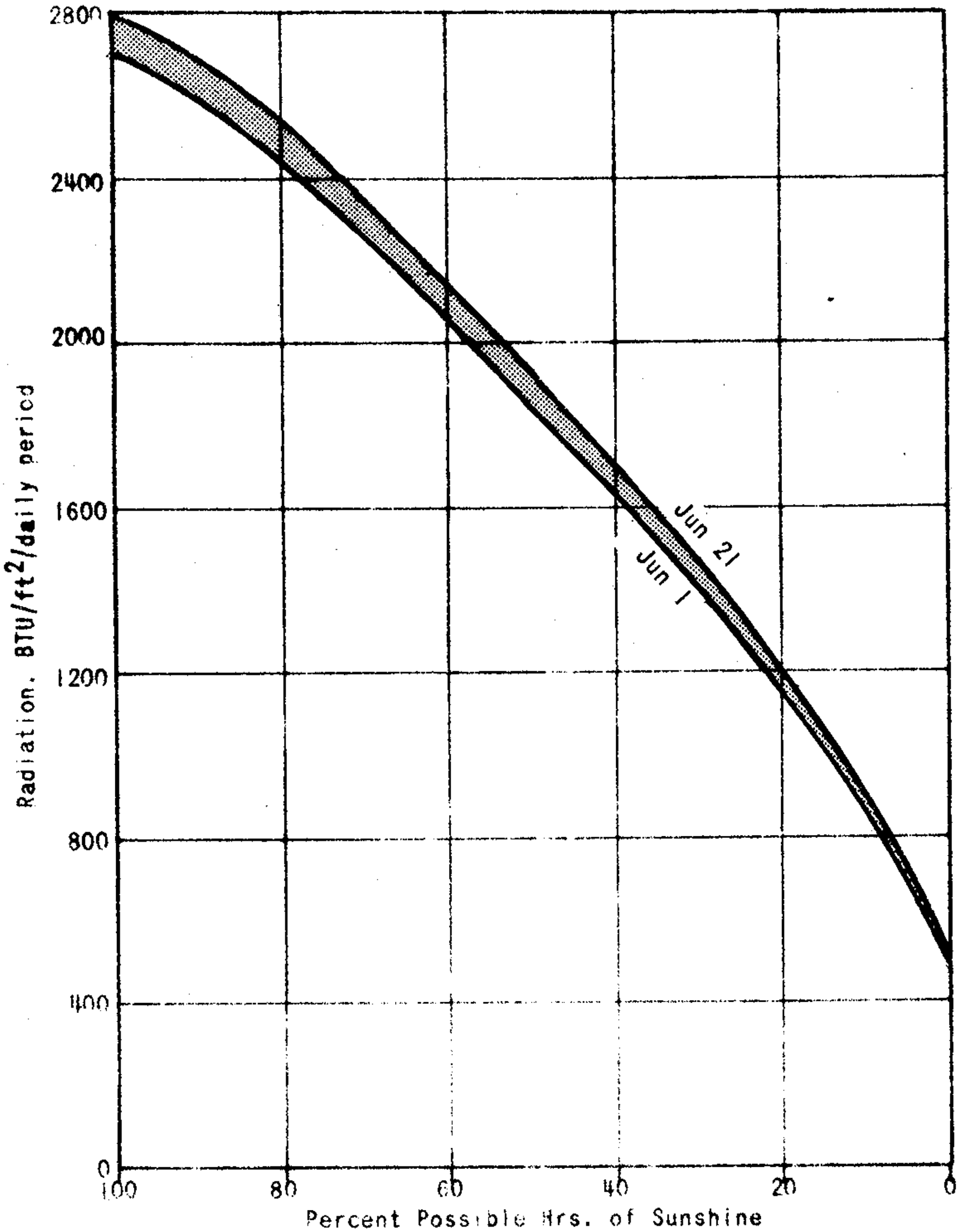
```
      IF(TH2O(N,M).GT.100..OR.TH2O(N,M).LT.30.) GO TO 11
      GO TO 16
   11 WRITE(6,18)TH2O(N,M)
   18 FORMAT(8X,15HTEMP TOO HIGH =,E16.7)
      TH2O(N,M) = 60.
   16 WRITE(6,12) M,TH2O(N,I),TH2O(N,M)
   12 FORMAT(8X,I2,2X,5H*****,2X,16HTEMP. AT START =,F6.2,2X,
     1  14HTEMP. AT END =,F6.2)
      RETURN
      END
$IBFTC DTRIB
      SUBROUTINE TRIB
      COMMON RM,VEL,TIME,ALAG,K,TA,TH2O,DRY,WET,XWIND,DEND,
     1    FLO,N,M,I,J,DHG,TDHG
      CALL TEMP
      M=M+1
      I=M-1
      RM(M)=RM(I)
      TH2O(N,M)=(FLO(I)*TH2O(N,I)+DHG(N,J)*TDHG(N,J))/(FLO(I)+
     1  DHG(N,J))
      RETURN
      END
$IBFTC DDISCG
      SUBROUTINE DISCG
      COMMON RM,VEL,TIME,ALAG,K,TA,TH2O,DRY,WET,XWIND,DEND,
     1  FLO,N,M,I,J,QP,TPDHG
      CALL TEMP
      M=M+1
      I=M-1
      RM(M)=RM(I)
      TH2O(N,M)=((FLO(I)-QP( J))*TH2O(N,I)+QP( J)*TPDHG( J))/
     1  FLO(I)
      RETURN
      END
$IBFTC DRESVR
      SUBROUTINE RESVR
      COMMON RM,VEL,TIME,ALAG,K,TA,TH2O,DRY,WET,XWIND,DEND,
     1  FLO,N,M,I,J,QP,TPDHG
      CALL TEMP
      M=M+1
      I=M-1
      RM(M)=RM(I)
      TH2O(N,M)=TH2O(N,I)
      RETURN
      END
```

APPENDIX C

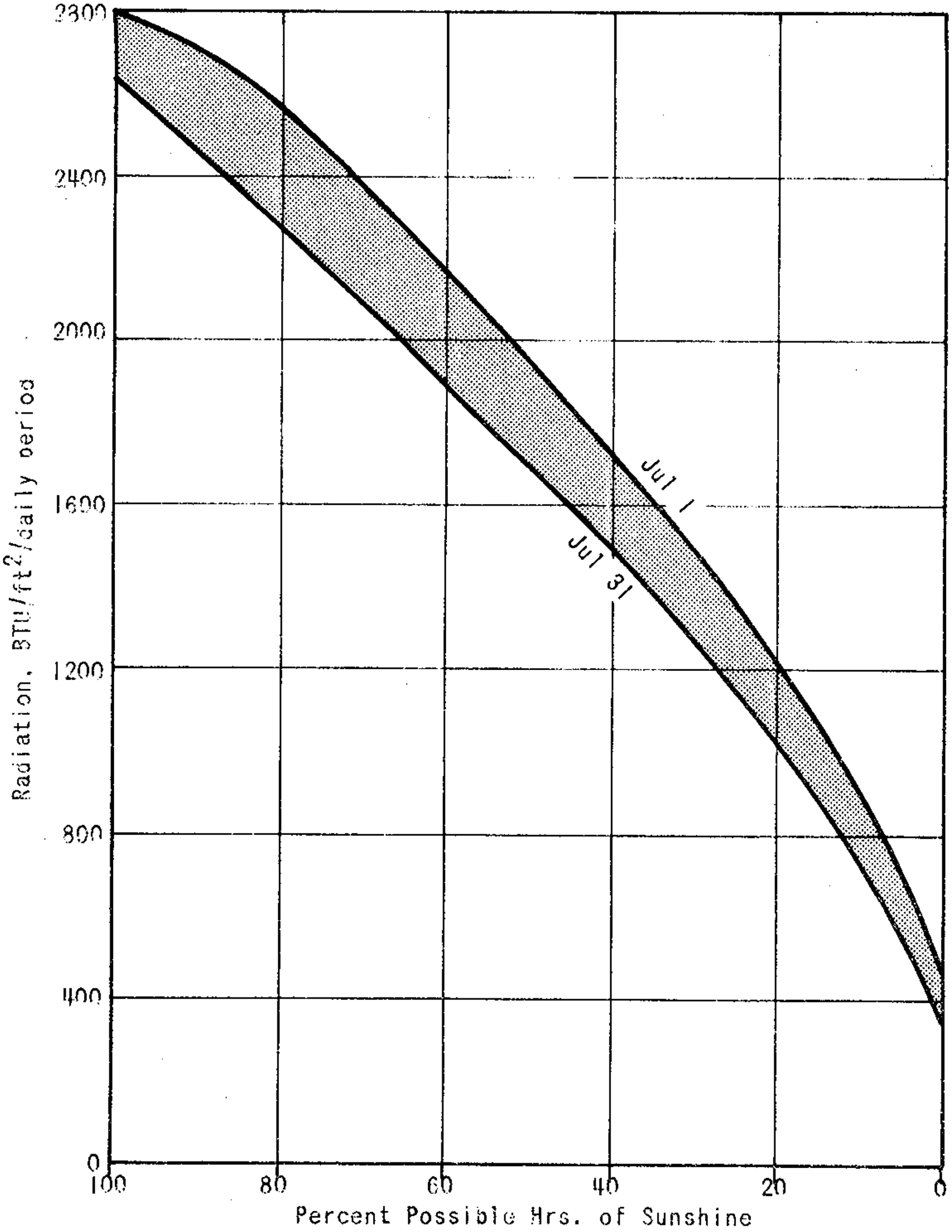
Expected Variation in Radiation Input



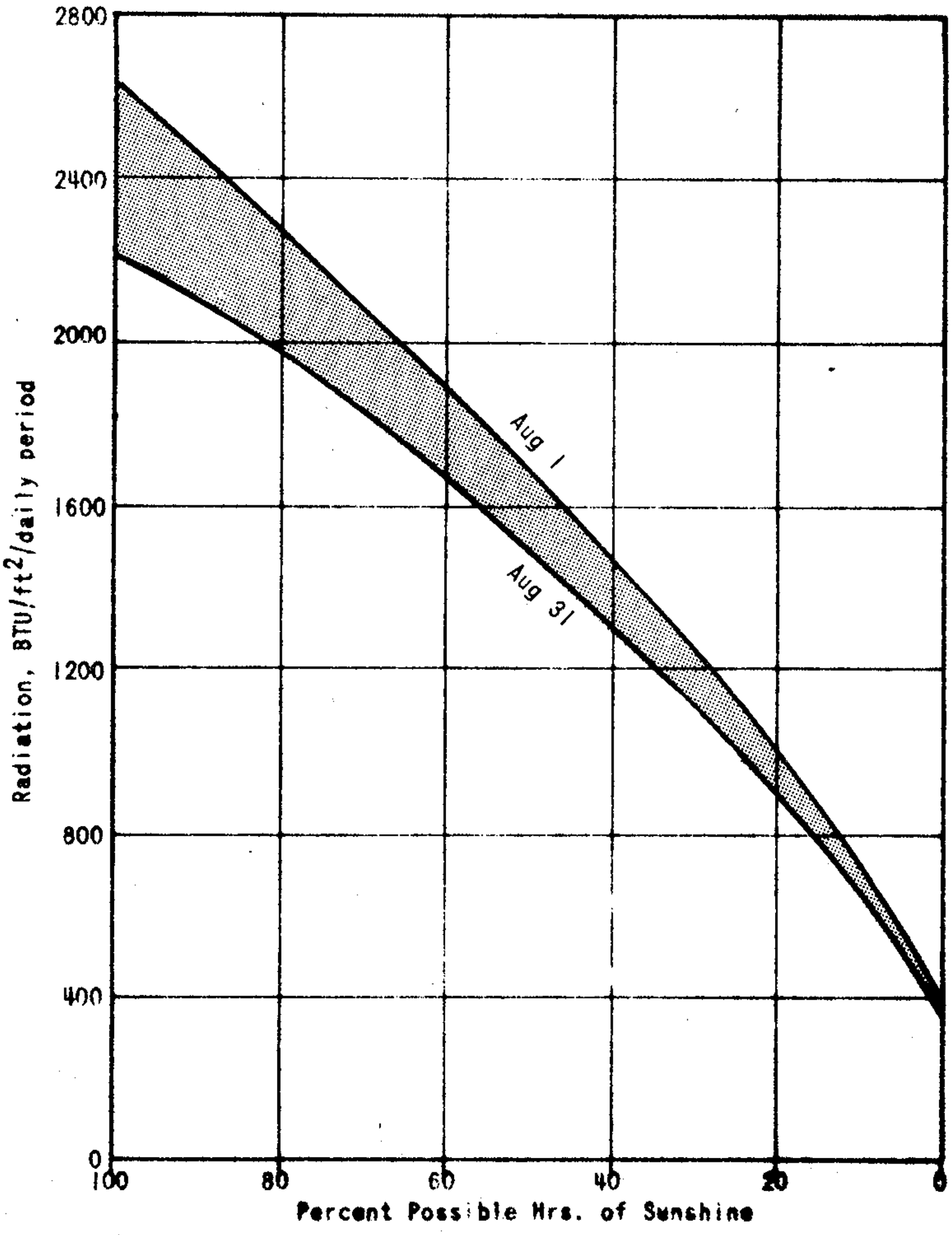
Expected Variation in Radiation Input



Expected Variation in Radiation Input



Expected Variation in Radiation Input



Expected Variation in Radiation Input

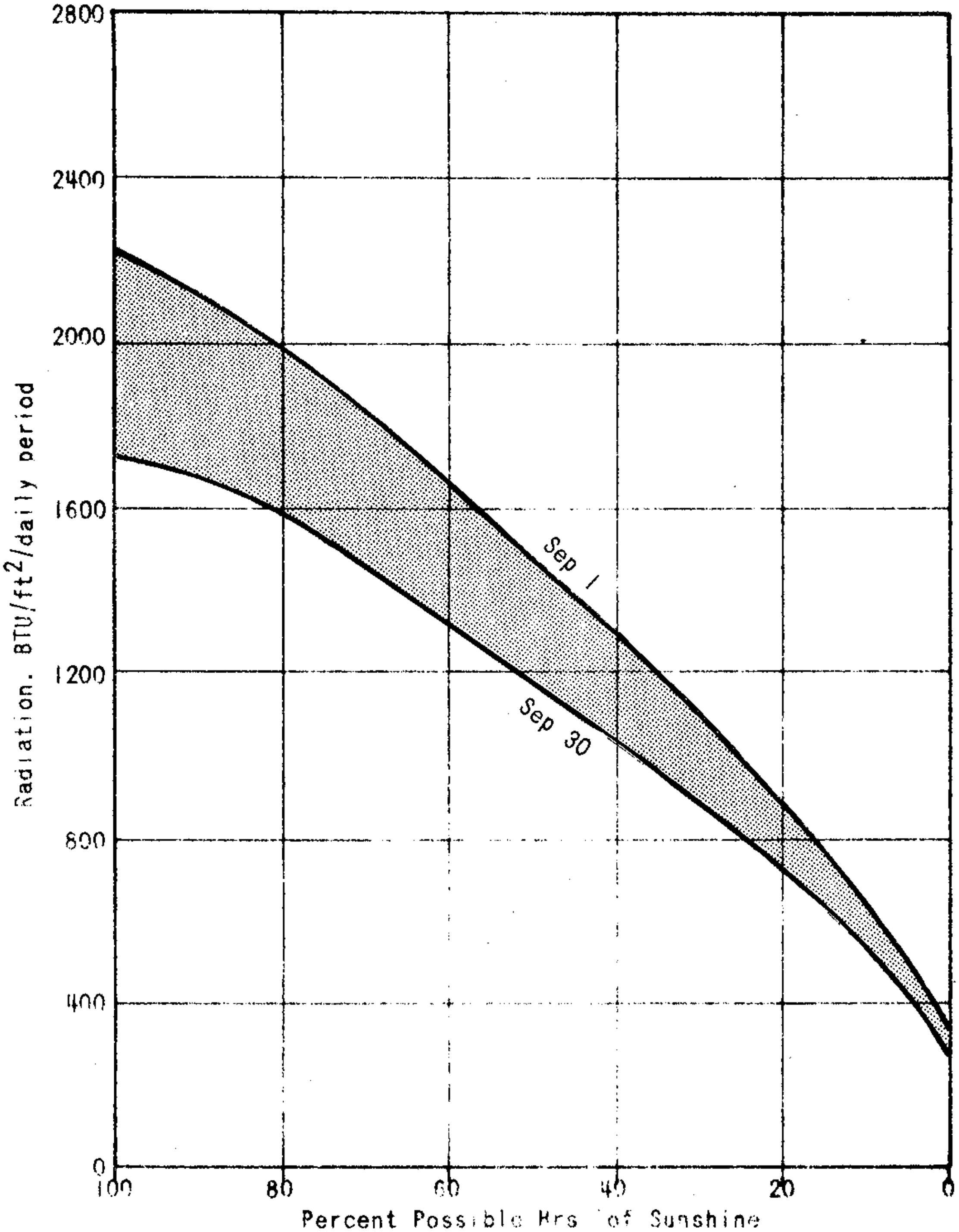


Table C.1 Radiation Input Data
Given in BTU/sq.ft./daily period

5	10	2616.	2490.	2333.	2156.	1940.	1720.	1530.	1300.	1080.	760.	390.
5	11	2617.	2499.	2335.	2165.	1947.	1729.	1536.	1308.	1083.	765.	391.
5	12	2624.	2508.	2340.	2170.	1954.	1738.	1546.	1316.	1086.	770.	392.
5	13	2631.	2517.	2354.	2175.	1961.	1747.	1554.	1324.	1089.	775.	393.
5	14	2638.	2526.	2362.	2180.	1968.	1756.	1562.	1332.	1092.	780.	394.
5	17	2639.	2535.	2355.	2195.	1969.	1783.	1586.	1356.	1101.	795.	397.
5	18	2658.	2552.	2394.	2200.	1996.	1792.	1594.	1364.	1104.	800.	398.
5	19	2670.	2571.	2402.	2205.	2003.	1801.	1602.	1372.	1107.	805.	399.
5	20	2680.	2580.	2410.	2210.	2010.	1810.	1610.	1380.	1110.	810.	400.
5	21	2684.	2585.	2417.	2213.	2014.	1811.	1611.	1382.	1111.	811.	401.
5	24	2690.	2600.	2436.	2242.	2026.	1814.	1614.	1388.	1114.	814.	404.
5	25	2700.	2605.	2445.	2250.	2030.	1815.	1615.	1390.	1115.	815.	405.
5	26	2704.	2619.	2452.	2256.	2034.	1816.	1616.	1392.	1116.	816.	406.
5	27	2708.	2615.	2459.	2265.	2038.	1817.	1617.	1394.	1117.	817.	407.
5	28	2712.	2620.	2456.	2274.	2042.	1818.	1618.	1396.	1118.	818.	408.
5	31	2724.	2635.	2437.	2291.	2054.	1821.	1621.	1402.	1121.	821.	410.
6	1	2728.	2640.	2490.	2291.	2060.	1825.	1621.	1410.	1125.	825.	410.
6	2	2731.	2643.	2494.	2292.	2066.	1832.	1622.	1412.	1128.	825.	410.
6	3	2734.	2645.	2495.	2293.	2099.	1838.	1623.	1413.	1129.	824.	410.
6	4	2737.	2649.	2498.	2294.	2112.	1844.	1924.	1414.	1131.	824.	410.
6	7	2747.	2658.	2504.	2297.	2151.	1862.	1627.	1417.	1135.	822.	410.
6	8	2750.	2661.	2505.	2298.	2164.	1868.	1628.	1418.	1137.	822.	410.
6	9	2755.	2665.	2508.	2299.	2177.	1874.	1629.	1419.	1138.	821.	410.
6	10	2760.	2670.	2510.	2300.	2190.	1880.	1630.	1420.	1140.	820.	410.
6	11	2763.	2673.	2512.	2302.	2192.	1883.	1632.	1422.	1141.	821.	411.
6	14	2772.	2682.	2515.	2308.	2198.	1892.	1638.	1428.	1144.	824.	414.
6	15	2775.	2685.	2520.	2310.	2200.	1895.	1640.	1430.	1145.	825.	415.
6	16	2775.	2688.	2522.	2312.	2202.	1898.	1642.	1432.	1146.	826.	416.
6	17	2781.	2691.	2524.	2314.	2204.	1901.	1644.	1434.	1147.	827.	417.
6	18	2754.	2694.	2526.	2316.	2206.	1904.	1646.	1436.	1148.	828.	418.
6	21	2755.	2697.	2528.	2318.	2208.	1399.	1648.	1438.	1149.	829.	419.
6	22	2752.	2694.	2526.	2316.	2206.	1388.	1646.	1436.	1148.	828.	418.

Table C.1 Continued

6	23	2778.	2691.	2524.	2314.	2204.	1877.	1644.	1434.	1147.	827.	417.
6	24	2774.	2688.	2522.	2312.	2202.	1866.	1642.	1432.	1146.	826.	416.
6	25	2770.	2685.	2520.	2310.	2200.	1855.	1640.	1430.	1145.	825.	415.
6	28	2758.	2676.	2514.	2304.	2194.	1822.	1634.	1424.	1142.	822.	412.
6	29	2754.	2673.	2512.	2302.	2192.	1811.	1632.	1422.	1141.	821.	411.
6	30	2750.	2670.	2510.	2300.	2190.	1800.	1630.	1420.	1140.	820.	410.
7	1	2745.	2662.	2501.	2291.	2080.	1798.	1626.	1411.	1136.	814.	407.
7	2	2740.	2654.	2492.	2282.	2070.	1796.	1622.	1402.	1132.	808.	404.
7	5	2725.	2630.	2465.	2255.	2040.	1790.	1610.	1375.	1120.	790.	395.
7	6	2720.	2622.	2456.	2246.	2030.	1788.	1606.	1366.	1116.	784.	392.
7	7	2715.	2614.	2447.	2237.	2020.	1786.	1602.	1357.	1112.	778.	389.
7	8	2710.	2606.	2438.	2228.	2010.	1784.	1598.	1348.	1108.	772.	386.
7	9	2705.	2598.	2429.	2219.	2000.	1782.	1594.	1339.	1104.	766.	383.
7	12	2686.	2572.	2408.	2200.	1976.	1774.	1582.	1322.	1092.	754.	382.
7	13	2679.	2563.	2402.	2195.	1969.	1771.	1578.	1318.	1088.	751.	383.
7	14	2672.	2554.	2396.	2190.	1962.	1768.	1574.	1314.	1084.	748.	384.
7	15	2665.	2545.	2390.	2185.	1955.	1765.	1570.	1310.	1080.	745.	385.
7	16	2658.	2536.	2384.	2180.	1948.	1762.	1566.	1306.	1076.	742.	386.
7	19	2637.	2509.	2366.	2165.	1927.	1753.	1554.	1294.	1064.	733.	389.
7	20	2630.	2500.	2360.	2160.	1920.	1750.	1550.	1290.	1060.	730.	370.
7	21	2620.	2492.	2353.	2154.	1913.	1745.	1545.	1286.	1056.	729.	369.
7	22	2610.	2484.	2346.	2148.	1906.	1740.	1540.	1282.	1052.	728.	368.
7	23	2600.	2475.	2339.	2142.	1899.	1735.	1535.	1278.	1048.	727.	367.
7	26	2570.	2452.	2318.	2124.	1878.	1720.	1520.	1266.	1036.	724.	364.
7	27	2560.	2444.	2311.	2118.	1871.	1715.	1515.	1262.	1032.	723.	363.
7	28	2550.	2436.	2304.	2112.	1864.	1710.	1510.	1258.	1028.	722.	362.
7	29	2540.	2428.	2297.	2106.	1857.	1705.	1505.	1254.	1024.	721.	361.
7	30	2530.	2420.	2290.	2100.	1850.	1700.	1500.	1250.	1020.	720.	360.
8	2	2511.	2400.	2272.	2080.	1842.	1686.	1486.	1242.	1016.	718.	362.
8	3	2503.	2390.	2263.	2070.	1838.	1679.	1479.	1238.	1014.	717.	363.
8	4	2494.	2380.	2254.	2060.	1834.	1672.	1472.	1234.	1012.	716.	364.
8	5	2485.	2370.	2245.	2050.	1830.	1665.	1465.	1230.	1010.	715.	365.

Table C.1 Continued

8	8	2476.	2350.	2238.	2040.	1826.	1658.	1458.	1226.	1008.	714.	366.
8	9	2449.	2330.	2209.	2010.	1814.	1637.	1437.	1214.	1002.	711.	369.
8	10	2440.	2320.	2200.	2000.	1810.	1630.	1430.	1210.	1000.	710.	370.
8	11	2428.	2309.	2190.	1993.	1804.	1624.	1424.	1207.	996.	709.	369.
8	12	2416.	2298.	2180.	1986.	1798.	1618.	1418.	1204.	992.	708.	368.
8	13	2404.	2287.	2170.	1979.	1792.	1612.	1412.	1201.	988.	707.	367.
8	16	2368.	2254.	2140.	1958.	1774.	1594.	1394.	1192.	976.	704.	364.
8	17	2356.	2243.	2130.	1951.	1768.	1588.	1388.	1189.	972.	703.	363.
8	18	2344.	2232.	2120.	1944.	1762.	1582.	1382.	1186.	968.	702.	362.
8	19	2332.	2221.	2110.	1937.	1756.	1576.	1376.	1183.	964.	701.	361.
8	20	2320.	2210.	2100.	1930.	1750.	1570.	1370.	1180.	960.	700.	360.
8	23	2287.	2183.	2070.	1905.	1729.	2149.	1352.	1162.	945.	691.	357.
8	24	2276.	2174.	2060.	1898.	1722.	2142.	1346.	1156.	940.	688.	356.
8	25	2265.	2165.	2050.	1890.	1715.	2135.	1340.	1150.	935.	685.	355.
8	26	2254.	2156.	2040.	1882.	1708.	2128.	1334.	1144.	930.	682.	354.
8	27	2243.	2147.	2030.	1874.	1701.	1521.	1328.	1138.	925.	679.	353.
8	30	2210.	2120.	2000.	1850.	1680.	1500.	1310.	1120.	910.	670.	350.
8	31	2200.	2116.	1985.	1837.	1667.	1490.	1302.	1115.	908.	666.	349.
9	1	2188.	2116.	1985.	1837.	1667.	1490.	1302.	1115.	908.	666.	349.
9	2	2176.	2012.	1970.	1824.	1654.	1480.	1294.	1110.	906.	662.	348.
9	3	2164.	2008.	1955.	1811.	1641.	1470.	1786.	1105.	904.	658.	347.
9	6	2128.	1995.	1910.	1772.	1602.	1440.	1262.	1090.	898.	646.	344.
9	7	2116.	1992.	1895.	1759.	1589.	1430.	1254.	1085.	896.	642.	343.
9	8	2104.	1988.	1880.	1746.	1576.	1420.	1246.	1080.	894.	638.	342.
9	9	2092.	1934.	1865.	1733.	1563.	1410.	1238.	1075.	892.	634.	341.
9	10	2080.	1930.	1850.	1720.	1550.	1400.	1230.	1070.	890.	630.	340.
9	13	2023.	1935.	1811.	1684.	1520.	1370.	1203.	1046.	869.	621.	335.
9	14	2006.	1920.	1798.	1672.	1510.	1360.	1194.	1038.	862.	618.	334.
9	15	1990.	1905.	1785.	1660.	1500.	1350.	1185.	1030.	855.	615.	332.
9	16	1972.	1890.	1772.	1648.	1490.	1340.	1176.	1022.	848.	612.	331.
9	17	1954.	1875.	1759.	1636.	1480.	1330.	1167.	1014.	841.	609.	329.
9	20	1900.	1830.	1720.	1600.	1450.	1300.	1140.	990.	820.	600.	325.

Table C.1 Continued

9	21	1883.	1814.	1704.	1585.	1435.	1288.	1129.	981.	813.	593.	322.
9	22	1866.	1798.	1688.	1570.	1420.	1276.	1118.	922.	806.	586.	320.
9	23	1849.	1782.	1672.	1555.	1405.	1264.	1107.	963.	799.	579.	317.
9	24	1832.	1766.	1656.	1540.	1390.	1252.	1096.	954.	792.	5 2.	315.
9	27	1781.	1718.	1608.	1495.	1345.	1216.	1063.	927.	771.	551.	307.
9	29	1747.	1686.	1575.	1465.	1315.	1192.	1041.	909.	757.	537.	302.
9	30	1730.	1670.	1560.	1450.	1300.	1180.	1030.	900.	750.	530.	300.

Table C.2 Air Temperatures at Designated Stations
21 Stations for each of 103 days
Given in Degrees Fahrenheit

51065.	64.56.57.67.57.66.66.66.77.77.66.78.70.70.71.71.70.71.69.71.66.	1.
51165.	67.67.56.71.71.79.81.82.59.60.82.61.61.60.61.60.59.59.69.62.82.	2.
51265.	59.64.60.58.58.58.60.53.74.75.58.75.73.70.74.74.72.72.70.71.58.	3.
51365.	62.64.62.63.63.65.66.66.53.53.66.53.54.54.54.53.51.55.54.54.66.	4.
51465.	55.55.47.45.45.46.47.48.68.68.48.67.67.67.69.65.65.65.66.66.48.	5.
51765.	73.72.69.69.69.70.72.75.72.72.75.72.72.71.69.72.71.71.70.70.75.	6.
51865.	56.59.61.58.58.57.57.58.65.65.58.64.64.65.59.58.58.55.54.54.58.	7.
51965.	65.65.66.71.71.70.70.71.64.64.71.64.63.63.62.59.57.56.57.57.71.	8.
52065.	59.58.56.55.55.54.54.54.67.67.54.67.68.68.69.72.72.70.66.70.54.	9.
52165.	79.80.80.78.78.77.76.73.72.72.73.71.71.72.72.69.69.66.75.66.73.	10.
52465.	60.64.65.69.69.71.74.75.78.80.75.80.80.81.80.79.78.75.75.75.75.	11.
52565.	79.76.76.73.73.72.70.72.38.39.72.40.40.41.41.44.45.48.48.49.72.	12.
52665.	70.71.75.75.75.76.76.79.85.83.79.84.85.85.85.84.84.84.83.81.79.	13.
52765.	70.71.71.71.71.72.72.72.73.72.72.72.70.70.68.67.62.61.61.61.72.	14.
52865.	70.70.69.68.68.67.67.66.79.79.66.79.80.80.77.77.77.76.76.76.66.	15.
53165.	71.71.71.72.72.75.75.75.75.75.75.71.71.71.70.69.68.67.67.66.75.	16.
60165.	47.46.46.44.44.45.45.44.44.44.74.73.73.73.71.71.69.68.67.67.66.	17.
60265.	69.69.70.69.69.69.69.69.69.69.68.68.68.68.67.67.67.66.66.66.65.	18.
60365.	50.50.51.52.52.53.54.54.55.55.71.70.70.70.70.70.69.69.69.69.68.	19.
60465.	80.80.80.80.80.81.81.81.81.81.74.74.74.73.73.71.70.70.70.69.68.	20.
60765.	73.72.69.68.68.67.66.66.65.65.76.76.76.76.76.76.76.77.77.77.77.	21.
60865.	82.82.82.82.82.84.85.85.85.85.68.70.70.70.71.72.73.73.73.73.73.	22.
60965.	68.68.68.71.71.72.72.72.73.73.73.83.83.84.84.80.83.82.82.82.81.	23.
61065.	75.76.77.78.78.79.79.79.79.79.71.70.70.70.69.68.68.67.67.67.67.	24.
61165.	72.70.68.68.65.68.68.67.66.66.73.73.73.73.73.73.74.75.75.75.75.	25.
61465.	70.70.69.68.68.67.67.67.67.67.61.61.60.60.60.60.60.60.59.59.59.	26.
61565.	59.57.57.57.57.58.58.58.58.58.69.69.69.69.68.67.67.67.67.67.67.	27.
61665.	79.79.78.79.79.79.79.79.79.79.72.71.70.70.70.70.69.67.66.66.66.	28.
61765.	59.59.58.58.58.57.57.57.57.57.79.79.79.79.80.78.78.78.77.77.76.	29.
61865.	65.65.65.63.63.63.63.63.63.63.57.57.57.57.57.58.58.58.58.58.58.	30.
62165.	74.72.72.70.70.69.69.69.69.69.86.86.86.87.88.88.87.87.87.87.87.	31.
62265.	92.92.92.92.92.93.93.93.93.93.62.62.62.63.63.64.64.64.64.64.65.	32.

Table C.2 Continued

62365.	75.74.73.72.72.71.71.70.69.69.81.81.83.83.83.82.82.82.83.83.83.	33.
62465.	75.76.82.79.79.79.79.79.79.79.65.65.67.65.66.66.66.67.67.67.68.	34.
62565.	71.69.69.68.68.68.67.67.67.67.77.77.78.78.78.78.78.78.75.75.75.	35.
62865.	90.90.89.89.89.88.88.88.88.88.65.66.66.67.67.68.76.76.77.77.78.	36.
62965.	71.71.70.70.70.71.70.70.70.70.89.89.89.88.88.87.87.85.84.84.84.	37.
63065.	77.77.77.77.77.77.77.77.77.77.67.68.68.68.68.69.69.70.70.70.70.	38.
70165.	51.49.49.48.48.48.48.48.48.48.82.82.78.78.77.77.77.77.76.76.76.	39.
70265.	85.85.85.84.84.84.84.84.84.84.51.51.51.52.52.54.54.55.56.56.57.	40.
70565.	64.63.62.61.61.61.60.60.60.60.68.68.68.69.70.70.71.71.72.72.72.	41.
70665.	73.73.73.74.74.74.74.74.75.75.58.58.58.58.58.59.59.59.59.59.59.	42.
70765.	55.54.53.52.52.52.52.51.49.49.76.76.76.76.76.76.75.75.73.73.73.	43.
70865.	61.61.61.62.62.62.62.62.62.62.58.58.58.58.58.62.62.62.62.62.63.	44.
70965.	61.60.59.58.58.58.58.58.57.57.73.76.78.78.79.80.80.80.81.81.81.	45.
71265.	84.84.84.83.83.83.82.82.82.82.54.54.54.55.55.57.58.60.61.61.61.	46.
71365.	53.52.50.50.50.49.49.49.48.48.87.87.87.86.86.86.85.84.84.84.84.	47.
71465.	82.82.82.81.81.81.81.81.81.81.74.74.74.74.75.75.75.76.76.76.77.	48.
71565.	67.67.66.65.65.65.65.65.64.64.84.84.84.84.84.83.83.83.82.82.82.	49.
71665.	86.86.86.85.85.85.85.85.84.84.62.63.63.63.64.68.69.69.70.70.70.	50.
71965.	69.67.64.63.63.63.63.63.62.62.82.80.81.82.82.82.82.82.81.81.80.	51.
72065.	70.70.70.71.71.71.72.72.72.72.45.45.46.46.49.50.50.50.51.51.50.	52.
72165.	60.59.58.55.55.53.52.52.51.51.77.75.75.76.76.76.76.75.75.75.75.	53.
72265.	78.78.79.80.80.80.81.81.82.82.44.44.44.44.45.46.46.46.46.46.47.	54.
72365.	71.70.70.69.69.69.69.68.67.67.80.80.80.80.82.82.83.83.82.82.82.	55.
72665.	84.84.83.83.83.82.82.82.82.82.63.63.64.64.64.65.64.64.64.64.64.	56.
72765.	51.50.49.49.49.49.48.48.48.48.71.71.71.71.70.70.70.71.71.71.71.	57.
72865.	71.71.71.70.70.70.69.69.69.69.56.56.56.56.57.57.58.58.59.59.59.	58.
72965.	60.58.56.55.55.55.54.54.54.54.79.79.79.79.78.78.78.78.77.77.77.	59.
73065.	85.85.85.86.86.86.85.85.85.85.52.52.53.53.53.54.55.56.56.57.57.	60.
80265.	63.63.63.62.62.62.62.62.62.62.76.76.76.76.76.76.75.74.74.74.74.	61.
80365.	72.72.72.74.74.74.74.74.74.74.57.57.57.57.57.58.58.58.58.59.59.	62.
80465.	65.64.63.61.60.60.59.59.59.59.82.82.82.82.83.83.83.83.82.82.82.	63.
80565.	87.87.87.88.88.88.88.88.88.88.46.46.46.46.47.47.47.47.48.48.48.	64.

Table C.2 Continued

80865.	60.59.58.57.57.57.57.57.57.57.92.92.92.92.93.93.93.93.93.93.93.	65.
80965.	79.79.80.79.79.79.79.79.78.78.69.69.69.69.70.70.70.70.70.70.70.	66.
81065.	69.69.69.68.68.68.68.68.68.68.94.94.93.90.88.79.82.82.82.81.81.	67.
81165.	85.85.85.85.85.85.86.86.86.86.65.65.66.67.67.68.68.68.69.70.70.	68.
81265.	62.61.61.61.61.60.60.60.60.60.84.84.84.84.84.86.86.86.85.84.85.	69.
81365.	88.88.89.85.88.88.88.88.88.88.69.69.70.70.71.72.72.73.73.73.73.	70.
81665.	74.73.71.68.68.67.67.67.66.66.99.99.99.99.99.99.99.99.99.99.99.	71.
81765.	93.94.94.94.94.95.95.95.95.95.68.68.68.68.68.69.69.69.70.70.70.	72.
81865.	78.78.77.75.75.75.74.74.74.74.88.88.88.88.87.86.86.86.85.85.85.	73.
81965.	78.78.78.79.79.79.80.80.80.80.71.71.71.71.71.72.72.72.72.72.72.	74.
82065.	69.69.69.69.69.69.68.68.68.68.79.79.79.80.79.79.77.77.77.77.77.	75.
82365.	75.75.74.74.74.74.74.74.74.74.61.61.62.63.63.64.64.66.66.66.66.	76.
82465.	46.46.46.46.46.46.46.46.46.46.84.84.84.83.83.82.82.82.81.81.81.	77.
82565.	79.78.78.77.77.77.77.77.77.77.57.57.57.57.58.59.59.59.60.60.60.	78.
82665.	57.57.56.56.56.56.56.56.56.56.66.66.66.66.65.65.65.65.64.64.64.	79.
82765.	79.79.79.78.78.78.78.78.78.78.62.62.62.62.63.64.64.64.65.65.65.	80.
83065.	49.48.48.48.48.48.48.48.48.48.67.67.67.67.67.67.66.66.66.66.66.	81.
83165.	52.53.54.56.56.58.58.58.58.58.36.36.36.36.36.36.36.36.36.36.36.	82.
90165.	56.56.56.55.55.55.55.55.54.54.62.62.62.62.62.62.62.62.62.62.62.	83.
90265.	75.75.76.76.76.77.77.77.77.77.52.52.52.52.52.52.53.53.53.53.53.	84.
90365.	51.51.50.48.48.48.48.48.48.48.48.77.77.77.77.74.74.74.74.74.74.	85.
90565.	78.78.79.79.79.78.78.78.78.78.78.48.48.48.49.50.51.51.51.51.52.	86.
90765.	47.47.47.47.47.47.47.47.47.47.47.77.77.76.76.75.75.75.74.74.74.	87.
90865.	74.73.73.73.73.75.75.75.75.75.75.55.55.56.56.56.56.56.57.57.57.	88.
90965.	49.49.48.48.48.48.48.48.48.48.48.76.76.76.75.74.74.74.71.71.70.	89.
91065.	77.75.77.76.76.76.76.76.76.76.76.63.63.63.64.65.65.65.65.65.66.	90.
91365.	45.45.44.44.44.44.44.44.43.43.43.62.62.62.62.62.62.62.61.61.61.	91.
91465.	66.66.65.66.65.67.67.67.67.67.67.44.44.44.44.45.45.45.45.45.45.	92.
91565.	57.57.56.57.57.57.56.56.56.56.56.69.69.69.69.68.68.68.68.68.68.	93.
91665.	64.64.65.66.66.66.66.66.66.65.66.59.59.59.59.59.60.60.60.60.60.	94.
91765.	53.53.52.52.52.52.52.52.52.52.52.60.60.60.60.60.60.60.59.59.60.	95.
92065.	82.82.82.82.82.82.81.80.79.79.79.62.62.62.62.63.63.63.63.63.64.	96.

Table C.2 Continued

92105.	60.59.59.58.58.58.58.58.58.58.58.85.85.85.84.83.83.83.80.80.80.	97.
92205.	85.85.86.86.85.86.86.86.86.85.86.69.69.70.70.70.71.71.71.71.72.	98.
92305.	72.72.72.72.72.72.72.72.72.72.72.85.84.84.84.83.83.83.82.82.82.	99.
92405.	76.76.76.76.75.76.76.75.75.76.76.68.68.68.68.69.69.69.69.69.69.	100.
92785.	43.43.43.42.42.42.42.42.42.42.42.42.42.42.42.42.42.42.42.42.42.	101.
92905.	68.68.65.68.65.68.68.68.68.68.68.60.60.60.61.61.61.61.61.61.62.	102.
93005.	51.51.50.50.50.50.50.50.50.50.50.68.68.68.67.67.67.67.66.66.66.	103.

Table C.3 Water Temperatures at Designated Stations
21 Stations for each of 103 days
Given in Degrees Fahrenheit

51065.	61.55.56.55.55.58.55.55.54.57.59.57.61.56.60.57.56.56.57.58.59.	1.
51165.	62.62.62.62.62.62.63.61.61.63.54.51.51.50.50.51.51.50.50.49.49.	2.
51265.	59.58.54.53.54.54.54.52.52.55.60.58.60.57.58.56.56.57.57.58.58.	3.
51365.	61.60.55.55.56.56.56.56.56.56.50.52.49.53.51.48.48.48.46.46.46.	4.
51465.	53.51.50.47.47.49.50.49.49.49.55.52.55.52.53.52.52.52.54.54.54.	5.
51765.	59.59.59.59.59.58.59.58.56.57.55.55.55.54.53.53.52.51.51.51.51.	6.
51865.	56.56.56.55.56.54.54.54.55.54.57.56.56.55.54.53.53.53.52.53.53.	7.
51965.	55.55.55.55.54.54.55.54.53.54.51.50.51.51.51.50.50.50.48.49.49.	8.
52065.	55.45.45.52.52.52.52.52.52.52.56.57.56.57.58.57.57.57.58.58.57.	9.
52165.	62.61.61.63.60.65.64.65.62.62.56.55.56.55.55.54.50.50.49.47.47.	10.
52465.	56.55.54.55.50.54.54.52.52.54.57.55.58.57.55.55.55.55.56.55.55.	11.
52565.	64.65.63.63.62.64.63.62.62.63.48.50.45.49.44.48.47.46.45.45.44.	12.
52665.	60.60.60.50.58.60.61.61.59.61.64.62.63.62.62.62.62.62.63.62.60.	13.
52765.	66.66.66.67.66.67.68.66.64.68.53.59.54.59.52.56.55.53.52.51.50.	14.
52865.	64.64.64.62.61.62.61.61.59.60.66.65.66.65.62.62.62.62.61.61.61.	15.
53165.	60.59.59.58.58.58.58.57.55.56.51.50.52.50.50.49.48.47.46.46.45.	16.
60165.	57.56.54.52.53.53.52.51.50.50.58.60.61.61.60.59.58.58.56.56.55.	17.
60265.	59.56.56.56.55.56.56.56.55.56.52.54.50.54.49.51.50.49.50.49.47.	18.
60365.	55.54.53.53.52.52.52.50.52.50.60.58.56.57.57.58.58.58.57.57.56.	19.
60465.	60.60.60.60.57.60.60.59.62.60.51.52.50.51.49.50.50.50.50.49.48.	20.
60765.	67.66.65.62.63.62.62.60.62.62.69.72.69.72.69.68.66.65.65.62.59.	21.
60865.	75.75.75.76.72.76.75.73.72.73.63.65.59.64.60.59.57.56.55.53.51.	22.
60965.	70.70.69.68.67.68.68.67.69.68.69.70.70.70.69.68.66.64.66.65.63.	23.
61065.	74.74.74.73.72.73.73.71.69.72.65.64.65.64.60.57.56.55.53.53.53.	24.
61165.	68.67.64.62.60.62.62.61.60.61.65.66.63.64.64.62.61.60.60.59.58.	25.
61465.	59.58.57.56.54.56.55.55.56.56.51.52.50.51.49.50.48.48.47.47.46.	26.
61565.	62.65.65.55.52.54.53.53.53.53.57.59.57.59.57.55.54.54.52.52.51.	27.
61665.	66.61.62.62.59.62.63.60.57.64.54.55.53.55.52.52.50.49.49.48.47.	28.
61765.	56.55.54.52.52.52.52.52.52.52.65.64.63.64.60.60.59.59.58.57.55.	29.
61865.	61.61.59.59.58.59.59.59.58.59.54.57.50.56.53.52.50.50.50.50.49.	30.
62165.	68.67.66.64.64.64.64.64.64.64.72.68.68.70.65.69.66.65.66.64.62.	31.
62265.	75.76.75.77.75.77.79.76.73.78.61.65.60.64.57.60.59.58.56.56.56.	32.

Table C.3 Continued

62365.	72.	70.	70.	67.	65.	65.	66.	65.	65.	66.	71.	69.	66.	69.	66.	59.	64.	64.	66.	65.	64.	33.
62465.	75.	75.	77.	74.	73.	74.	73.	72.	70.	73.	63.	66.	64.	66.	62.	62.	60.	58.	57.	57.	58.	34.
62565.	69.	68.	66.	63.	63.	62.	62.	62.	63.	62.	66.	67.	63.	64.	61.	65.	60.	59.	64.	63.	62.	35.
62865.	74.	72.	74.	71.	74.	76.	72.	71.	69.	74.	57.	61.	56.	61.	58.	60.	57.	56.	63.	61.	58.	36.
62965.	70.	70.	70.	70.	70.	70.	68.	67.	65.	68.	62.	79.	74.	77.	69.	75.	73.	70.	67.	67.	68.	37.
63065.	74.	74.	73.	72.	73.	72.	72.	71.	70.	72.	65.	68.	63.	67.	61.	64.	61.	61.	61.	61.	60.	38.
70165.	66.	66.	65.	63.	63.	63.	62.	60.	58.	60.	74.	70.	68.	73.	67.	70.	69.	68.	66.	66.	66.	39.
70265.	74.	70.	73.	72.	75.	73.	70.	70.	70.	74.	54.	61.	54.	60.	55.	57.	56.	55.	55.	55.	54.	40.
70565.	65.	60.	66.	64.	64.	64.	63.	63.	64.	64.	60.	62.	59.	63.	60.	62.	60.	56.	62.	61.	60.	41.
70665.	72.	72.	72.	72.	69.	73.	73.	72.	70.	72.	58.	62.	59.	61.	56.	59.	56.	56.	57.	57.	56.	42.
70765.	65.	64.	62.	61.	61.	61.	60.	60.	60.	60.	65.	64.	62.	65.	62.	64.	59.	58.	66.	65.	64.	43.
70865.	73.	73.	73.	73.	70.	73.	75.	73.	70.	74.	58.	61.	58.	61.	59.	59.	58.	57.	59.	58.	57.	44.
70965.	66.	66.	66.	64.	64.	64.	64.	64.	64.	65.	70.	68.	66.	69.	66.	70.	66.	64.	69.	68.	67.	45.
71265.	75.	74.	77.	72.	76.	75.	73.	73.	72.	75.	58.	63.	57.	64.	58.	60.	58.	59.	60.	58.	55.	46.
71365.	68.	68.	67.	66.	64.	66.	64.	63.	61.	64.	79.	75.	72.	77.	66.	74.	70.	69.	68.	69.	71.	47.
71465.	76.	76.	76.	74.	76.	76.	73.	73.	72.	74.	63.	68.	63.	67.	63.	65.	63.	61.	64.	62.	60.	48.
71565.	74.	73.	72.	70.	70.	70.	68.	67.	66.	68.	76.	77.	74.	78.	70.	75.	70.	69.	67.	67.	66.	49.
71665.	75.	76.	79.	76.	78.	76.	73.	74.	76.	78.	57.	64.	58.	64.	60.	62.	59.	60.	62.	59.	56.	50.
71965.	67.	67.	66.	67.	63.	67.	66.	66.	66.	65.	70.	68.	69.	70.	64.	68.	67.	62.	67.	65.	62.	51.
72065.	70.	70.	70.	69.	66.	68.	67.	66.	65.	65.	54.	60.	55.	59.	55.	57.	56.	58.	55.	54.	52.	52.
72165.	65.	64.	62.	61.	59.	60.	60.	60.	60.	60.	68.	67.	66.	67.	64.	65.	62.	60.	67.	64.	61.	53.
72265.	72.	72.	71.	70.	69.	70.	69.	68.	67.	72.	55.	60.	55.	60.	55.	56.	56.	56.	54.	53.	52.	54.
72365.	67.	67.	67.	65.	64.	66.	65.	64.	63.	64.	65.	65.	63.	64.	60.	64.	62.	60.	63.	63.	63.	55.
72665.	75.	73.	66.	74.	76.	75.	73.	72.	71.	73.	60.	65.	59.	65.	60.	63.	60.	63.	60.	55.	55.	56.
72765.	70.	69.	66.	66.	62.	65.	64.	63.	61.	62.	70.	68.	69.	68.	67.	66.	64.	66.	62.	61.	60.	57.
72865.	70.	70.	69.	67.	66.	68.	66.	65.	65.	66.	55.	61.	57.	61.	58.	60.	58.	60.	58.	57.	55.	58.
72965.	67.	66.	64.	63.	61.	63.	61.	61.	60.	60.	69.	67.	64.	66.	60.	66.	63.	62.	62.	57.	63.	59.
73065.	76.	74.	76.	72.	74.	74.	72.	72.	71.	72.	53.	58.	55.	58.	52.	58.	56.	57.	58.	50.	52.	60.
80265.	66.	60.	63.	63.	62.	63.	63.	63.	62.	63.	61.	63.	60.	61.	58.	59.	59.	58.	59.	54.	57.	61.
80365.	67.	67.	67.	69.	64.	69.	67.	66.	64.	66.	58.	60.	57.	59.	55.	58.	57.	56.	57.	55.	55.	62.
80465.	64.	62.	61.	61.	57.	60.	59.	59.	59.	58.	66.	64.	66.	65.	60.	66.	64.	60.	67.	66.	64.	63.
80565.	76.	71.	76.	75.	74.	75.	74.	73.	71.	77.	53.	58.	53.	58.	55.	56.	54.	57.	52.	48.	48.	64.

Table C.3 Continued

80565.	57.	56.	55.	54.	60.	65.	63.	63.	62.	61.	70.	70.	70.	70.	61.	72.	69.	64.	71.	64.	64.	65.
80965.	74.	74.	73.	73.	73.	73.	72.	71.	69.	69.	64.	67.	61.	67.	60.	65.	64.	64.	62.	57.	61.	66.
81065.	72.	71.	71.	71.	69.	70.	70.	70.	70.	68.	60.	77.	72.	76.	68.	75.	70.	67.	66.	63.	65.	67.
81165.	75.	75.	75.	74.	71.	74.	74.	73.	71.	73.	63.	66.	61.	66.	59.	63.	61.	60.	61.	55.	58.	68.
81265.	66.	66.	66.	65.	61.	64.	64.	65.	62.	64.	74.	72.	71.	74.	65.	72.	67.	69.	66.	62.	67.	69.
81365.	75.	75.	77.	76.	75.	74.	74.	73.	72.	74.	64.	67.	63.	66.	60.	64.	62.	61.	62.	57.	62.	70.
81565.	77.	76.	75.	73.	72.	73.	73.	72.	73.	70.	76.	76.	76.	78.	66.	80.	77.	68.	73.	73.	73.	71.
81765.	84.	82.	86.	80.	83.	65.	83.	81.	78.	85.	66.	72.	66.	71.	64.	68.	66.	65.	62.	57.	57.	72.
81865.	74.	76.	75.	76.	75.	76.	76.	75.	73.	73.	76.	76.	71.	74.	69.	73.	71.	68.	68.	67.	72.	73.
81965.	76.	76.	76.	75.	71.	75.	75.	74.	72.	75.	68.	72.	69.	72.	62.	68.	66.	64.	67.	67.	66.	74.
82065.	74.	72.	71.	69.	69.	69.	68.	68.	68.	69.	70.	69.	69.	70.	66.	68.	68.	68.	65.	64.	62.	75.
82365.	70.	70.	70.	79.	70.	70.	70.	70.	71.	73.	60.	63.	61.	63.	60.	61.	60.	59.	63.	61.	58.	76.
82465.	64.	64.	63.	63.	60.	62.	62.	61.	60.	60.	70.	70.	65.	72.	61.	68.	65.	66.	63.	62.	61.	77.
82565.	71.	67.	71.	70.	67.	69.	66.	65.	64.	68.	55.	60.	57.	60.	55.	58.	56.	56.	59.	55.	55.	78.
82665.	66.	66.	66.	64.	63.	64.	64.	64.	63.	62.	60.	62.	60.	61.	59.	60.	59.	57.	60.	58.	56.	79.
82765.	67.	67.	69.	67.	67.	66.	65.	65.	64.	70.	69.	61.	60.	60.	58.	60.	58.	57.	61.	59.	57.	80.
83065.	58.	57.	55.	53.	52.	53.	53.	53.	53.	53.	57.	57.	56.	58.	55.	58.	55.	53.	59.	56.	52.	81.
83165.	55.	55.	55.	55.	54.	55.	55.	55.	54.	55.	52.	51.	50.	51.	47.	51.	50.	49.	51.	49.	47.	82.
90165.	55.	54.	54.	54.	52.	54.	54.	53.	52.	54.	52.	53.	53.	53.	52.	53.	53.	52.	54.	53.	52.	83.
90265.	62.	62.	62.	62.	60.	62.	62.	61.	60.	62.	52.	52.	52.	52.	51.	52.	52.	51.	52.	51.	50.	84.
90365.	58.	58.	56.	55.	55.	56.	55.	54.	53.	55.	63.	59.	59.	59.	56.	59.	58.	58.	56.	56.	57.	85.
90665.	56.	63.	57.	56.	58.	56.	64.	64.	65.	66.	51.	56.	52.	56.	53.	56.	54.	54.	56.	55.	53.	86.
90765.	63.	62.	62.	61.	59.	60.	60.	59.	58.	60.	72.	68.	62.	71.	59.	67.	64.	66.	61.	61.	61.	87.
90865.	64.	63.	64.	64.	63.	64.	62.	62.	61.	64.	57.	61.	55.	61.	56.	58.	56.	56.	57.	56.	55.	88.
90965.	61.	61.	60.	60.	58.	60.	59.	59.	58.	56.	69.	67.	61.	67.	58.	64.	62.	63.	59.	61.	63.	89.
91065.	65.	65.	68.	70.	67.	69.	67.	67.	66.	70.	59.	62.	59.	62.	57.	60.	59.	59.	59.	59.	59.	90.
91365.	57.	57.	56.	56.	53.	56.	55.	55.	55.	55.	51.	53.	51.	53.	51.	52.	52.	52.	52.	52.	51.	91.
91465.	58.	58.	57.	56.	55.	56.	57.	57.	56.	55.	48.	50.	47.	50.	48.	49.	49.	49.	48.	48.	48.	92.
91565.	57.	56.	56.	55.	55.	55.	55.	55.	55.	54.	56.	54.	53.	54.	53.	54.	54.	54.	53.	53.	53.	93.
91665.	62.	62.	62.	62.	61.	61.	62.	61.	60.	62.	53.	54.	53.	54.	53.	54.	53.	52.	53.	53.	52.	94.
91765.	56.	56.	56.	55.	55.	55.	54.	54.	53.	54.	58.	56.	55.	55.	55.	56.	55.	55.	53.	53.	54.	95.
92065.	63.	62.	64.	64.	64.	64.	64.	63.	62.	56.	56.	56.	55.	56.	55.	55.	54.	54.	53.	53.	54.	96.

Table C.3 Continued

92165.	62.62.62.60.55.60.61.61.60.60.73.69.65.68.63.69.66.64.64.63.61.	97.
92265.	72.71.73.71.74.70.70.69.68.70.61.63.59.62.58.62.60.59.60.58.56.	98.
92365.	69.69.69.68.67.68.68.67.65.67.75.71.70.71.64.70.68.66.64.63.61.	99.
92465.	65.65.66.66.68.67.67.67.67.69.62.66.61.66.58.60.60.59.54.53.52.	100.
92765.	54.54.54.53.52.53.53.53.54.52.53.52.52.52.52.52.52.52.52.52.52.	101.
92965.	57.57.56.56.55.56.56.55.55.56.50.50.50.55.50.51.50.50.50.50.50.	102.
93065.	52.52.52.51.49.51.51.51.50.51.60.56.54.56.52.55.55.55.51.52.53.	103.

Table C.4 Wind Speeds (From U.S.Weather Bureau, Lebanon , N.H.)
Given in miles per 24 hr. period

51065	20.	51165	10.	51265	35.	51365	10.	51465	25.
51765	10.	51865	5.	51965	10.	52065	5.	52165	15.
52465	15.	52565	15.	52665	15.	52765	15.	52865	15.
53165	5.	60165	25.	60265	20.	60365	5.	60465	15.
60765	20.	60865	15.	60965	10.	61065	10.	61165	40.
61465	15.	61565	5.	61665	5.	61765	15.	61865	15.
62165	20.	62265	45.	62365	3.	62465	42.	62565	40.
62865	35.	62965	45.	63065	25.	70165	5.	70265	30.
70565	10.	70665	25.	70765	40.	70865	75.	70965	30.
71265	15.	71365	15.	71465	55.	71565	45.	71665	25.
71965	30.	72065	25.	72165	20.	72265	10.	72365	20.
72665	10.	72765	25.	72865	35.	72865	35.	72965	15.
80265	40.	80365	15.	80465	55.	80565	35.	80665	15.
80965	35.	81065	60.	81165	40.	81265	20.	81365	25.
81665	55.	81765	10.	81865	30.	81965	50.	82065	45.
82365	20.	82465	25.	82565	20.	82665	30.	82765	20.
83065	30.	83165	40.	90165	35.	90265	90.	90365	20.
90665	25.	90765	5.	90865	20.	90965	15.	91065	45.
91365	10.	91465	15.	91565	10.	91665	65.	91765	35.
92065	15.	92165	45.	92265	40.	92365	30.	92465	40.
92765	35.	92965	50.	93065	20.				

Table C.5 Wet & Dry Bulb Temperatures & Cloud Cover
(From U.S.Weather Bureau, Lebanon, N.H.)
Given in °F. and tenths of complete cloud cover

Average Value for each Quarter of the day

			1st		2nd		3rd		4th		1st	2nd	3rd	4th
			Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet				
5	10	65	56.5	55.0	60.0	59.1	86.0	64.8	73.8	65.0	5	10	5	6
5	11	65	59.0	56.1	57.2	57.1	74.9	59.0	65.2	52.0	10	10	8	1
5	12	65	52.5	46.0	51.6	48.1	74.0	55.5	61.8	54.4	0	0	0	3
5	13	65	45.0	43.9	53.2	50.0	58.5	51.0	58.2	43.5	0	7	7	0
5	14	65	32.0	31.1	39.7	37.5	65.0	49.0	61.8	45.0	0	0	0	0
5	17	65	60.0	60.0	58.3	58.0	66.1	63.2	68.0	60.0	10	10	10	10
5	18	65	54.9	51.8	53.0	51.6	67.9	59.1	57.6	53.2	8	10	10	10
5	19	65	52.8	51.2	53.5	51.5	57.8	53.1	63.0	56.1	10	10	10	10
5	20	65	45.5	45.0	52.0	52.0	73.2	62.8	66.0	53.0	0	10	4	2
5	21	65	38.3	38.2	43.9	41.5	71.0	55.0	66.1	57.1	0	0	4	7
5	24	65	33.1	32.8	35.0	34.9	63.1	48.4	70.2	51.5	0	4	0	9
5	25	65	39.0	38.8	42.7	42.0	78.0	58.2	77.0	62.0	0	8	10	8
5	26	65	57.0	56.0	65.0	62.3	84.9	68.1	73.0	65.1	0	7	10	10
5	27	65	63.7	59.1	56.0	49.1	70.0	59.9	66.8	66.5	0	10	10	10
5	28	65	66.0	66.0	60.3	60.3	71.9	58.1	70.4	53.8	10	8	2	3
5	31	65	45.2	45.0	42.0	42.0	52.0	49.0	60.0	52.9	10	0	9	5
6	1	65	40.8	40.8	43.5	43.5	64.0	48.0	66.2	51.4	0	10	5	10
6	2	65	51.3	51.2	54.0	53.0	55.0	54.8	54.8	54.2	10	10	10	10
6	3	65	46.0	46.0	47.0	43.0	60.8	48.1	50.2	45.8	4	0	3	7
6	4	65	39.2	39.2	46.0	46.0	70.1	53.5	71.1	55.1	0	0	4	0
6	7	65	57.0	56.2	63.1	60.2	59.8	74.7	76.4	79.	0	3	9	10
6	8	65	64.2	64.0	53.4	63.2	73.2	70.0	83.0	69.0	4	2	7	5
6	9	65	64.2	63.8	64.0	64.0	70.0	68.0	71.0	64.0	10	10	3	8
6	10	65	60.3	60.3	66.4	60.2	72.4	68.5	65.0	56.0	10	10	6	3
6	11	65	46.8	46.4	52.8	50.2	71.7	55.5	68.8	56.1	0	0	5	8
6	14	65	47.7	47.7	50.0	49.1	52.0	51.0	53.8	52.8	10	10	10	10
6	15	65	46.1	48.1	45.1	46.0	60.2	54.0	54.5	52.5	10	10	8	3
6	16	65	44.0	44.0	45.0	45.0	70.5	55.8	67.0	57.0	10	10	5	5
6	17	65	42.8	42.8	44.0	44.0	57.1	54.2	71.9	58.2	0	10	2	10
6	18	65	48.0	48.0	54.0	53.0	60.0	58.2	62.6	59.0	10	9	10	3
6	21	65	61.0	57.0	70.0	62.5	67.0	69.5	60.9	68.0	0	9	10	10
6	22	65	54.9	53.0	70.0	64.5	81.5	63.0	76.5	63.4	2	0	0	3

Table C.5 Continued

6	23	65	59.2	51.9	57.0	55.0	67.2	66.0	66.8	65.0	0	3	10	10
6	24	65	55.5	55.3	56.8	64.0	75.0	59.1	63.6	56.5	10	10	3	3
6	25	65	52.5	52.2	55.9	52.0	67.0	53.8	64.0	51.3	4	0	4	0
6	28	65	60.0	53.5	50.5	55.5	83.7	70.0	64.8	70.0	0	0	3	10
6	29	65	76.4	56.7	71.5	64.3	84.0	68.0	80.0	65.2	2	8	5	10
6	30	65	64.4	52.1	55.2	63.1	69.0	63.0	67.7	58.8	10	10	10	8
7	1	65	46.5	46.5	51.8	51.2	74.0	56.0	70.2	56.2	0	0	1	0
7	2	65	44.5	44.2	43.0	43.0	72.6	58.2	61.2	61.0	0	10	2	9
7	5	65	51.0	51.0	52.0	52.0	65.6	64.5	67.2	65.4	0	10	10	10
7	6	65	52.0	52.0	57.2	54.0	54.2	51.0	62.8	53.5	10	3	0	1
7	7	65	41.5	41.5	42.5	42.2	69.0	58.0	69.8	60.5	0	9	8	9
7	8	65	62.0	62.0	63.0	62.0	76.0	66.0	80.2	62.1	10	10	3	3
7	9	65	52.4	51.9	56.9	55.0	84.0	66.0	78.5	68.1	1	10	10	8
7	12	65	55.2	55.2	52.0	52.0	75.3	60.5	77.8	61.5	2	10	4	3
7	13	65	51.6	51.6	55.0	55.0	83.3	65.7	78.7	64.1	6	2	7	7
7	14	65	66.2	62.0	72.0	66.0	87.8	71.8	75.5	70.5	2	5	7	10
7	15	65	69.8	67.6	71.0	65.0	76.8	61.3	75.0	60.0	10	8	8	0
7	16	65	51.7	51.5	55.5	54.4	81.8	62.3	78.0	62.0	0	0	0	6
7	19	65	62.5	62.8	60.9	59.6	70.3	56.3	68.2	55.0	10	2	6	2
7	20	65	45.5	45.2	45.9	43.9	65.0	58.7	66.0	55.0	0	4	9	7
7	21	65	45.2	45.0	44.6	44.8	69.0	58.4	75.0	58.3	0	10	2	7
7	22	65	47.6	47.6	47.2	47.2	76.8	58.3	75.8	63.0	0	10	8	10
7	23	65	62.0	62.0	65.5	62.0	72.2	64.1	71.0	66.7	10	10	10	10
7	26	65	55.8	55.8	60.0	58.5	77.1	60.4	75.0	58.9	0	0	7	5
7	27	65	51.7	51.5	56.6	53.2	78.2	55.3	61.3	56.0	0	8	6	3
7	28	65	51.2	51.2	52.9	52.9	72.0	58.0	72.8	60.9	10	10	8	8
7	29	65	55.5	52.5	57.9	55.1	72.0	58.0	67.6	58.8	4	5	6	9
7	30	65	48.2	48.2	49.8	49.6	75.8	60.2	72.6	58.6	0	10	7	5
8	2	65	65.0	65.9	65.9	59.6	63.8	58.9	66.5	60.0	10	10	10	9
8	3	65	59.0	56.0	59.0	52.1	69.5	60.9	67.0	58.0	10	10	10	9
8	4	65	51.0	49.0	55.5	52.2	74.9	59.1	66.6	58.1	0	0	4	4
8	5	65	51.0	50.0	49.0	49.0	62.9	62.8	75.8	61.2	4	0	1	3

Table C.5 Continued

8	8	65	66.1	53.0	56.1	57.0	68.2	66.8	83.6	66.2	2	2	2	2
8	9	65	70.0	69.8	71.9	70.5	75.8	73.1	77.3	77.0	10	10	10	8
8	10	65	72.7	71.2	71.0	70.0	60.0	73.0	66.8	66.3	10	6	7	10
8	11	65	55.2	55.2	56.2	57.5	75.0	65.0	65.0	59.8	10	10	6	0
8	12	65	53.5	50.5	52.6	52.0	73.8	63.0	63.9	60.5	0	10	0	8
8	13	65	70.3	63.2	67.1	65.5	61.9	67.6	73.0	65.0	8	8	5	3
8	16	65	55.0	54.0	63.8	53.5	92.0	70.0	87.1	73.2	0	2	0	1
8	17	65	56.5	55.0	69.6	68.0	84.0	72.0	88.0	77.0	0	9	4	3
8	18	65	74.9	70.8	69.6	69.0	86.2	74.4	84.2	74.8	8	10	10	2
8	19	65	71.3	70.3	71.9	69.6	79.0	74.0	69.0	67.0	6	10	10	8
8	20	65	61.5	61.5	63.0	62.0	73.8	60.2	65.2	58.0	10	5	7	0
8	23	65	59.0	59.0	60.0	60.0	73.0	59.2	68.2	56.2	10	9	3	0
8	24	65	45.0	43.0	45.1	45.1	72.2	60.0	74.8	60.2	0	10	4	3
8	25	65	49.0	49.0	50.0	50.0	76.0	63.0	71.6	63.9	0	8	10	10
8	26	65	61.0	59.0	62.0	59.0	62.9	60.0	61.8	60.5	3	10	10	10
8	27	65	61.5	61.5	62.3	62.3	75.0	67.8	77.4	67.3	10	10	10	3
8	30	65	42.5	39.5	46.8	41.5	57.9	46.8	53.0	44.0	0	2	2	1
8	31	65	32.9	32.8	33.1	33.0	42.6	41.5	63.5	49.5	0	10	10	10
9	1	65	55.0	53.0	52.9	52.5	61.0	60.9	65.0	65.0	10	10	10	10
9	2	65	50.2	55.8	51.2	51.2	58.0	58.0	72.0	59.0	10	7	1	5
9	3	65	47.0	47.0	47.0	47.0	69.0	60.0	65.3	60.0	10	10	0	2
9	6	65	45.0	45.0	45.9	45.9	77.0	65.0	67.3	62.0	2	10	0	2
9	7	65	52.1	52.1	53.2	53.2	71.2	61.8	65.9	59.9	3	10	3	0
9	8	65	52.0	52.6	53.5	53.5	55.8	64.2	58.3	57.0	8	10	10	0
9	9	65	48.2	48.2	51.0	51.0	63.0	59.8	70.3	64.4	10	10	8	8
9	10	65	61.2	60.1	65.5	63.0	69.2	67.0	84.8	73.0	10	10	10	0
9	13	65	41.0	40.0	44.2	44.0	48.9	48.8	47.8	47.8	10	10	10	10
9	14	65	40.7	46.7	48.0	48.0	58.7	52.8	60.3	58.1	10	10	10	10
9	15	65	55.3	56.5	56.5	56.5	63.5	59.6	62.6	62.3	10	5	10	10
9	16	65	55.9	63.2	55.1	55.0	65.0	55.6	55.0	51.2	5	1	7	7
9	17	65	40.5	43.8	45.0	45.0	64.0	52.0	58.8	53.0	8	10	9	8
9	20	65	56.0	57.4	59.5	58.8	68.8	65.0	79.6	72.8	10	10	4	1

Table C.5 Continued

9	21	65	69.3	69.2	68.6	68.1	83.0	73.0	80.3	70.2	4	8	3	0
9	22	65	70.5	69.2	66.5	66.0	83.0	74.0	79.3	73.1	0	8	0	0
9	23	65	71.7	70.2	70.3	69.0	85.0	74.0	72.9	69.2	0	5	1	2
9	24	65	70.0	67.2	67.2	65.2	60.0	60.0	61.0	60.2	10	10	10	10
9	27	65	44.4	41.4	37.9	33.1	50.2	41.0	40.0	35.0	10	10	0	0
9	29	65	46.2	45.9	47.3	45.0	60.0	53.0	54.0	50.0	10	9	10	10
9	30	65	40.0	38.3	36.5	36.1	55.0	45.0	54.3	49.0	0	10	5	10

Table C.6 Stream Flows (From U.S.G.S. Water Supply Papers)
@ West Hartford, Vermont
Given in Cubic feet per second

51065	912.	51165	863.	51265	814.	51365	724.	51465	670.
51765	599.	51865	604.	51965	560.	52065	530.	52165	485.
52465	427.	52565	395.	52665	368.	52765	358.	52865	395.
53165	322.	60165	302.	60265	294.	60365	302.	60465	288.
60765	225.	60865	284.	60965	375.	61065	350.	61165	372.
61465	291.	61565	302.	61665	280.	61765	246.	61865	228.
62165	192.	62265	176.	62365	167.	62465	173.	62565	173.
62865	133.	62965	123.	63065	115.	70165	113.	70265	110.
70565	161.	70665	167.	70765	167.	70865	141.	70965	141.
71265	108.	71365	99.	71465	92.	71565	92.	71665	90.
71965	184.	72065	120.	72165	99.	72265	92.	72365	88.
72665	74.	72765	69.	72865	69.	72965	69.	73065	69.
80265	60.	80365	60.	80465	62.	80565	62.	80665	57.
80965	115.	81065	185.	81165	199.	81265	167.	81365	120.
81665	76.	81765	70.	81865	65.	81965	82.	82065	125.
82365	92.	82465	80.	82565	74.	82665	70.	82765	74.
83065	80.	83165	72.	90165	88.	90265	223.	90365	277.
90665	115.	90765	101.	90865	92.	90965	83.	91065	94.
91365	115.	91465	219.	91565	242.	91665	189.	91765	153.
92065	147.	92165	156.	92265	138.	92365	123.	92465	136.
92765	423.	92965	255.	93065	235.				

APPENDIX D

BIBLIOGRAPHY OF THE ENGINEERING ASPECTS OF ARTIFICIAL HEAT IN AN AQUATIC ENVIRONMENT

Albertson, O. L., Tichenor, B. A., Seaders, J., and Burgess, F. J., "Stream Temperature Prediction by Digital Computer Techniques," Report, Dept. of Civil Engineering, Oregon State University, Corvallis, Oregon, 97331.

American Society of Civil Engineers. 1965. River Bypass Boosts Efficiency of Power Plant, Civil Engr. 35(11); 88.

Anderson, E. A., Baker, D. R. "Estimating Incident Terrestial Radiation under all Atmospheric Conditions" Water Resources Research Vol. 3, No. 4, 4th Quarter 1967, p. 975.

Anderson, E. R., "Energy Budget Studies in Water-Loss Investigations," Lake Hefner Studies, Circular 229, Geological Survey, U. S. Dept. of the Interior, Washington, D. C., 1952.

Anderson, L. J., "Instrumentation for Mass-Transfer and Energy Budget Studies," Lake Hefner Studies, Circular 229, Geological Survey, U. S. Dept. of the Interior, Wash. D. C., Vol. 1, 1952.

Arnold, G. E., "Thermal Pollution of Surface Supplies," Journal, American Water Works Association, Vol. 54, Nov. 1962, p. 1332.

Bata, Geza L., "Recirculation of Cooling Waters in Rivers and Canals,", Journal of the Hydraulics Division, ASCE, Vol. 83, No. HY3, Proc. Paper 1265, June 1957.

Berger, Bernard B., "Does Production of Power Pollute Our Rivers?" Power Engineering, Mar. 1961, p. 60-61.

Berman, Leo Davedovich, "Evaporative Cooling of Circulating Water, Pergamon Press, N. Y. 1961.

Birge, E. A., Juday, C., and March, H. W. "The Temperature of the Bottom Deposits of Lake Mendota: a Chapter in the Heat Exchanges of the Lake," Transactions, Wisconsin Academy of Science, Arts and Letters, Vol. 23, 1927, pp. 187-231.

Blackman, R. B., and Tukey, J. W., 1958. The Measurement of Power Spectra, Dover Publications, Inc., N. Y.

Bolsenga, S. J., Daily sums of global radiation for cloudless skies, U. S. Army Cold Regions Res. Eng. Lab., Res. Rept., 160, 124 pp., 1964.

Bosen, J. F., 1960. Formula for Approximation of Saturation Vapor Pressure over Water, Monthly Weather Review, 88: 275-276 (August).

Bowden, K. F. "The Mixing Processes in a Tidal Estuary," Paper No. 33, Inter-National Conference on Water Pollution Research, London, Sept. 3-7, 1962.

Bowen, I. S., "The Ratio of Heat Losses by Conduction and by Evaporation from Any Water Surface," Physical Review, Vol. 27, No. 2, June 1926, pp. 779-787.

Boyer, Peter B., "Method of Computing Average Reservoir Temperature," Water Temperature, Influences, Effects and Control, Proceedings of the 12th Pacific Northwest Symposium on Water Pollution Research, Pacific Northwest Laboratory, U. S. Dept. of Health, Education and Welfare, 1963.

Bramhall, D. F. & Mills, ES. "Alternative Methods of Improving Stream Quality: An Economic & Policy Analysis" Water Resources Research, Vol. 2., No. 3, 3rd Qtr. 1966, p. 355.

Braswell, R. W. "A Cooling Pond Proves Cheaper," Electrical World, Nov. 1953.

British Electric Authority, Changes in Dissolved oxygen content of River Water used for Direct Cooling, Rep. No. 10 Generating Station, Operation Research Liaison Committee. British Elec. Auth. 1954.

Brutsaert, W., Equations for vapor flux as a fully turbulent diffusion process under adiabatic conditions, Bull. Intern. Assoc. Sci. Hydrol., 10 (2), 11-21, 1965.

Cadwallader, L. W., "Thermal Pollution of Streams," presented to the 15th Annual Meeting of the Virginia Water Pollution Control Assn. at Old Point Comfort, Va., May 8-9, 1961.

Cadwallader, L. M., "Thermal Pollution of Water Courses," Proceedings, 19th Industrial Waste Conference, at Purdue University, Lafayette, Ind. 1964, p. 9.

Chellis, R. D. and Ireland, E. "Site Studies for a Steam Power Plant," Journal of the Power Division, ASCE, Vol. 85, No. PO1, Proc. Paper 1949, Feb. 1959.

Churchill, M. A. "Control of Temperature Through Streamflow Regulation," Symposium on Streamflow Regulation for Quality Control, Cincinnati, Ohio, 1963.

Collins, W.D., 1925. Temperature of Water Available for Industrial Use, U.S. Geological Survey Water Supply Paper 520 (f), U.S. Gov't Printing Office, Washington, D.C.

Cootner, Paul H. "A Model for the Estimation of Water Demand for Steam Electric Generation", Water Resources for the Future, Inc., Preliminary Draft, undated.

Cory, Robert L., and Davis, Henry F. "Automatic Data System Aids Thermal Pollution Study of Patuxent River," Water and Sewage Works, Vol. 112, Apr. 1965, pp. 129-134.

Cotter, T.J. and Lotz, A.W. "Cooling Pond Design in the southwest " Journal of the Power Division, ASCE, Vol. 87, No. PO2, Proc. Paper 2861, July 1961, pp. 85-103.

Cross, W.P., Schroeder, M.E., and Norris, S.E., 1952. Water Resources of the Mahoning River Basin, Ohio, U.S. Geological Survey Circular 177, Washington, D.C.

Cummings, N.W., 1940. The Evaporation-Energy Equations and their Practical Application, Transactions, American Geo-physical Union, 21, Part 2: 512-522.

Davidson, B., Bradshaw, R., Thermal Pollution of Water Systems, Environmental Science and Technology, Aug., 1967.

Delay, William H. "Temperature Studies on the Umpqua River, Oregon," Water Temperature, Influences, Effects and Control, Proceedings of the 12th Pacific Northwest Symposium on Water Pollution Research, Pacific Northwest Laboratory, Public Health Service, U.S. Dept. of Health, Education and Welfare, 1963.

Dendy, J.S., Stroud, R.H., The Dominating influence of Fontana Reservoir on Temperature and Dissolved Oxygen in The Little Tennessee River and its Improvements. J. Tenn. Acad. Sci. 24 (1): 41-51.

DeTurville, C.M., and Jarman, R.T. "The Mixing of Warm Water from the Uskmouth Power Stations in the Estuary of the River Usk." International Journal of Air and Water Pollution, Pergamon Press, England, Vol. 9, 1965, pp. 239-251.

Dingman, S.L., W.F. Weeks, and Y.C. Yen, The effects of thermal pollution on river ice conditions: I-A general method of calculation, U.S. Army Cold Regions Res. Eng. Lab. Res. Rept. 206, 1967.

Duncan, A.J., 1959. Quality Control and Industrial Statistics, Revised Edition, Richard D. Irwin, Inc., Chicago, Ill.

Duttweiler, D.W. "A Mathematical Model of Stream Temperature," Thesis presented to The Johns Hopkins University at Baltimore, Md., in 1963, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Edinger, J.E. and Geyer, J.C. "Heat Exchange in the Environment," EEI Publication No. 65-902, Edison Electric Institute, June, 1965.

"Effect of Water Temperature on Stream Reaeration", Progress Report, Committee on Sanitary Engr. Research ASCE. Journal of the Sanitary Engineering Div. Proceedings of the ASCE. 87: 59-71 Nov. 1961.

Elder, J.W. "The Dispersion of Marked Fluid in Turbulent Shear Flow," Journal of Fluid Mechanics, Vol. 5, Part 4, May 1959.

Elder, R.A. "Thermal Density Currents and Their Utilization in Condensing Water Design," Engineering Laboratory, Division of Water Control Planning, T.V.A., Norris, Tenn. Apr. 1959.

Elder, R.A. "Thermal Density Underflow Design and Experience," Engineering Laboratory Division of Water Control Planning, T.V.A., Norris, Tenn. July 1958.

Elder, Rex A. and Dougherty, Gale B. "Thermal Density Underflow Diversion , Kingston Steam Plant," Journal of the Hydraulics Division, ASCE, Vol. 84, No. HY2, Proc. Paper 1583, Apr. 1958.

Eliassen, R., "Stream Pollution," Scientific American, Vol. 186, Mar. 1952, P. 17.

Elmore, H.E., West, W.F., Effect of Water Temperature on Stream Reaeration, (J. San. Engr. Div.) Proc., ASCE, 87 (SA6, Nov., Pt. 1) (Paper 2997) 1961: 59-71.

Engle, Melvin D. "Condensing Water - How Does it Affect the River?" Mechanical Engineering, Vol. 83, No. 1, Jan. 1961.

Everts, Curtiss M. "Temperature as a Water Quality Parameter," Water Temperature Influences, Effects, and Control, Proceedings of the 12th Pacific Northwest Symposium on Water Pollution Research, Pacific Northwest Water Laboratory, Public Health Service, U.S. Dept. of Health, Education and Welfare, 1963.

Fair, G.M., Moore, E.W., 1932. Heat and Energy Relations in the Digestion of Sewage Solids. III Effect of Temperature upon the course of Digestion. Sewage Works J. 4: 589.

Feigner, K. D., "An Evaluation of Temperature Reduction on Low Flow Augmentation Requirements for Dissolved Oxygen Control." M.S. Thesis, Oregon State Univ., June '63.

Fiehn, A. J., "Cooling Tower Solutions to Problems of Power Station Circulating Water System Design." Presented at ASCE Conference on Thermal Pollution, Oct. 1967.

Finnerty, J. J. 1961. Unusual applications of cooling towers. Ind. Water and Wastes, 6 (6): 187-190.

Foster, R. F., Junkins, R. L. and Linderoth, C. E. "Waste Control at the Hanford Plutonium Production Plant," a draft of report concerning work performed under Contract No. AT (45-1)-1350, between the U. S. Atomic Energy Commission and the General Electric Company, 1960.

Fritz, S. 1958. Seasonal Heat Storage in the Ocean and Heating of the Atmosphere. Archiv fur Meteorologie Geophysik und Bioclimatologie, Ser. A, 10(4): 291-300.

Gameson, A. L. H., Vandyke, K. G., Ogden, C. G. 1958. The Effect of Temperature on Aeration at Weirs., Water & Water Engr. 62: 489-492.

Gameson, A. L. H., Gibbs, J. W. and Barrett, M. S. "A Preliminary Temperature Survey of a Heated River," Water and Water Engineering London, Vol. 63, No. 755, Jan 1959, p. 13.

Gameson, A. L. H. Hall, and W. S. Preddy, 1957, "Effects of Heated Discharges on the Temperature of the Thames Estuary." The Engineer, Dec. 6, 13, 20, 1957.

Garay, P. N. "Design Considerations in Selecting Water Cooling Systems," Consulting Engineer, Vol. 26, No. 1, Jan. 1966, p. 92.

Geraghty, J. J., Power Struggle over Thermal Pollution in the Northwest, Water Newsletter, 9 (9), 4, 1967.

Gilberts, D. E. "Investigation of Thermal Additions to Rivers," Presented at the 38th Annual Meeting of the Central States Water Pollution Control Assn. held at Albert Lea, Minn. June 9-11, 1965.

Goitein, E. E. "Selection and Application of Cooling Towers in Steam-Electric Stations," Combustion, Vol. 29, No. 5, Nov. 1957, p. 38.

Goodell, Bertram C. "An Inexpensive Totalizer of Solar and Thermal Radiation," Journal of Geophysical Research, Vol. 67, No. 4, Apr. 1962.

Hall, L., Curtis G., Diffusion of Heated Condenser Water from a Nuclear Power Plant, Masters Thesis, M. I. T., Cambridge, Mass.

Hamon, Russell W.; Weiss, L. L.; Wilson, Walter T. "Insolation as an Empirical Function of Daily Sunshine Duration". Monthly Weather Review, June 1954. p. 141.

Harbeck, G. E. Jr. "A Practical Field Technique for Measuring Reservoir Evaporation Utilizing Mass-Transfer Theory," Professional Paper No. 272-E, Geological Survey, U. S. Dept. of the Interior, 1962, pp. 101-105.

Harbeck, G. E. Jr. "Surface Water Withdrawals: Theoretical Considerations, Water Loss Investigations," Lake Mead Studies, Professional Paper No. 298, Geological Survey, U. S. Dept. of the Interior, 1958.

Harbeck, G. E. Jr. "The Use of Reservoir and Lakes for the Dissipation of Heat," Circular No. 282, Geological Survey, U. S. Dept. of the Interior, 1953.

Harbeck, G. E. Jr. et al. "The Effect of the Addition of Heat from a Power Plant on the Thermal Structure and Evaporation of Lake Colorado City, Texas," Professional Paper No. 272-B, Geological Survey, U. S. Dept. of the Interior, U. S. Govt. Printing Office, Wash. D. C. 1959.

Harbeck, G. E. Jr. and Kennon, F. W. "The Water Budget Control," Lake Hefner Studies, Circular No. 229, Geological Survey, U. S. Dept. of the Interior, 1952.

Harbeck, G. E. Jr., Kohler, Max A., Koberg, Gordon E., et al., "Water-Loss Investigations," Lake Mead Studies, Professional Paper No. 298, Geological Survey, U. S. Dept. of the Interior, 1958.

Harding, S. T., 1942. "Evaporation from Free Water Surfaces, Chapter III in Hydrology (O. E. Meinzer, Ed.), McGraw-Hill, New York.

Hatfield, H. F. "Temperature Distribution in the Susquehanna River at Brunner Island, Steam Electric Station," Progress Report, EM-DEV-242, 1962.

Heat Dissipation in Flowing Streams," Report of the 1960-61 Advanced Seminar, Dept. of Sanitary Engineering and Water Resources, Johns Hopkins University, Baltimore, Md. Dec. 1961.

"Heated Discharges - Their Effect on Streams", Report by the Advisory Committee for the Control of Stream Temperatures to the Pennsylvania Sanitary Water Board, Division of Sanitary Engineering, Bureau of Environmental Health, Pennsylvania Dept. of Health, Harrisburg, Pa. Jan. 1962.

Herry, S. "Pollution of Rivers by Heated Discharges," Bull., Centre belge Et. Document, Eaux, Vol. 46, 1959, pp. 226-235.

Hickox, G. H. "Evaporation from a Free Water Surface", A. S. C. E., Transactions, Vol. III, paper 2266, 1946, pp. 1-33.

Hoak, Richard D. "Defining Thermal Pollution," Power Engineering, Dec. 1961.

Hoak, R. D. "Hot Water - A Growing Industry Concern," Industrial Water Engineering, Vol. 2, No. 4, Apr. 1965, p. 10.

Hoak, Richard D. "Thermal Loading of Streams", Water Resources Research Projects, Mellon Institute, Pittsburgh, Pa. 1962.

Hoak, Richard D. "The Thermal Pollution Problem", Journal, Water Pollution Control Federation, Vol. 33, No. 12, Dec. 1961, pp 1267-1276.

Holzman, B., "The Heat-Balance Method for the Determination of Evaporation from Water Surfaces", American Geophysical Union, Transactions, Vol. 22, pt. 3, 1941, pp. 655-659.

Huber, W. C., "Thermal Stratification and Water Quality in Reservoir Impoundments", Doctoral Dissertation M. I. T., Cambridge, Mass.

Hull, C. H. and Carbaugh, H. E. Report No. VI, Low-Flow Augmentation Project, Dept. of Sanitary Engineering and Water Resources, The Johns Hopkins University, Baltimore, Md. Aug. 31, 1959.

"Is Heat a Pollutant? Pennsylvania Thinks So." Chemical Engineering Progress, Vol. 56, June 1960, p. 33.

Jaske, R. T. "Some Observations of Columbia River and Reservoir Behavior from Hanford Experience," Water Temperature, Influences, Effects, and Control, Proceedings of the 12th Pacific Northwest Symposium on Water Pollution Research, Pacific Northwest Water Laboratory, Public Health Service, U. S. Dept. of Health, Education & Welfare, 1963.

Jaske, R. T. "Thermal Modification of River Water Quality". Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, Washington, Oct. 18, 1967. Prepared for presentation at the Sixth Biennial Hydraulics Conference, Pullman, Washington.

Jaske, R. T., & Spurgeon, J. L. "A Special Case, Thermal Digital Simulation of Waste Heat Discharges", Prepared for presentation at the 63rd National Meeting of the American Institute of Chemical Engineers, Preprint 35B.

Jaske, R. T. "The Use of Digital Systems Modeling in the Evaluation of Regional Water Quality Involving Single or Multiple Releases". Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, Washington. Aug. 1967. Presented Nov. 26-30, Am. Inst. of Ch. Engrs. meeting on Water Pollution Abatement.

Jaske, Robert T. "Effects of Dam Construction on Temperatures of the Columbia River." Journal AWWA, Vol. 59, No. 8. Aug. 1967.

Jaske, R. T. "A Test Simulation of the Temperatures of the Deerfield River." A. E. C. Research & Development Report Battelle Northwest Laboratory, Dec. 1967.

Jaske, R. T., et al. "Study Program To Determine The Potential Impact of Thermal Power Plants on Pacific Northwest Streams". Pacific Northwest Laboratories, a Div. of Battelle Memorial Institute, 3000 Stevens Drive, Richland, Washington, 99352

Kerr, S. L. and Moyer. "Hydraulic-Engineering Problems at Southwork Generating Station," Transactions, American Society of Mechanical Engineers, Vol. 64, No. 6, Aug. 1962, p. 529.

Kittrell, F. W., and Kochitzky, O. W. Jr. "Natural Purification Characteristics of a Shallow Turbulent Stream," Sewage Works Journal, Vol. 19, 1947, p. 1032.

Koberg, G. E. "Effect on Evaporation of Releases from Reservoirs on Salt River, Arizona", reprinted from Bulletin No. 19, Geological Survey, U. S. Dept. of the Interior, Denver, Colorado. 1960

Koberg, G. E. "Energy-Budget Studies in Water-Loss Investigations", Lake Mead Studies, Professional Paper, Geological Survey, U. S. Dept. of the Interior, 1958.

Koberg, G. E. "Methods to compute long-wave radiation from the Atmosphere and Reflected Solar Radiation from a water surface", U. S. Geological Survey Professional Paper, 272-F, 107-136, 1964.

Laberge, Ronald H., 1959. "Thermal Discharges Water and Sewage Works", Dec. 1959.

Lamb, N. "Report on the Behavior of Power Station Cooling Ponds," Projects Division, Power Development Branch, The Electricity Commission of New South Wales, Australia.

Lamoreux, W.W., 1962. Modern Evaporation Formulae Adapted to Computer Use, Monthly Weather Review, 90: 26-28 (January).

Langhaar, J.W., 1953. Cooling Pond May Answer Your Water Cooling Problem, Chemical Engineering, August, 194-198.

LeBosquet, M. "Cooling Water Benefits from Increased River Flows," Journal, New England Water Works Assn., Vol. 60, No. 2, June 1946, p. 11.

LeBourueau, John W. "Second Report of Deerfield River Study," Yankee Atomic Electric Co., 441 Stuart St., Boston, Mass. 1959

Leclerc, E. 1962. Self-purification of Fresh Water as Affected by Temperature and the Content of Oxygen, Nitrogen, and other Substances. J. Water Poll. Control Fed. 34 (3): 224

Leeds, J.V., Accuracy of Discrete Models to Predict Estuary Pollution, Water Resources Research, Vol. 3, No. 2, 1967, p. 481.

Lima, D.O. "Pond Cooling by Surface Evaporation," Power, Vol. 80, No. 3, 1936, pp. 142-144.

Long, R.R. "Some Aspects of the Flow of Stratified Fluids. I.A. Theoretical Investigation", Tech. Report No. 2, Dept. of Civil Engineering, The Johns Hopkins University, Baltimore, Md. 1953.

Long, R.R. "Some Aspects of the Flow of Stratified Fluids. II. Continuous Density Gradients", Tech. Report No. 6, Dept. of Civil Engineering, The Johns Hopkins University, Baltimore, Md. 1955.

Long, R.R. "The Motion of Fluids with Density Stratification", Journal of Geophysical Research, Vol. 64, No. 12, Dec. 1959.

Mackey, C.O., 1950. Heat Transmission, in Section 3, Kent's Mechanical Engineer's Handbook, Power Volume, 12th Edition, J.K. Salisbury, Editor, John Wiley and Sons, Inc., New York.

MacKichan, Kenneth A. "Estimated Use of Water in the United States, 1955. Circular 398. U.S. Geological Survey, 1957.

Marciano, J.J. and Harbeck, G.E. "Mass Transfer Studies", Vol. 1, Lake Hefner Studies, Circular No. 229, Geological Survey, U.S. Dept. of the Interior, 1952.

Mariner, L.T., and Hunsucker, W.A. "Ocean Cooling Water Systems for Two Thermal Plants", Journal of the Power Division, ASCE, Vol. 85, No. PO4, Proc. Paper 2133, Aug. 1959.

Markowski, S. "The Cooling Water of Power Stations; A New Factor in the Environment of Marine and Fresh-water Invertebrates," Journal of Animal Ecology, Vol. 28, No. 2, 1959, pp. 243-255.

Mathur, S.P., "Thermal Pollution From Steam Electric Generating Plants, F.W.P.C.A., Robert A. Taft, Sanitary Engineering Center, Cincinnati, Ohio.

McAlister, W.B. "Prediction of Stream Temperature Downstream from the Proposed Lost Creek Damsite," Rouge River Basin Study, Part II, State Water Resources Board, State of Oregon, May 1961.

McEwen, George F. "A Mathematical Theory of the Vertical Distribution of Temperature and Salinity in Water Under the Action of Radiation, Conduction, Evaporation and Mixing Due to the Resulting Convection," Bulletin, Scripps Institute of Oceanography, LaJolla, Calif., Technical Series 2, No. 6, University of California Press 1929.

Meeting Tomorrow's Power Needs, June 1960. Edison Electric Institute, Bulletin No. 60-36.

Messinger, H. "Dissipation of Heat from a Thermally Loaded Stream", Professional Paper No. 104, Geological Survey, U.S. Department of the Interior, 1963.

Meyer, A.F. "Evaporation from Lakes and Reservoirs," Minnesota Resources Commission, June 1942.

Millar, F.G. "Evaporation From Free Water Surfaces" Canada, Department of Transport, Division of Meteorological Services, Canadian Meteorological Memoirs, Vol. 1, No. 2, 1937, pp. 39-65.

Moore, A.M. "Instrumentation for Water-Temperature Studies," Water Temperature, Influences, Effects and Control Proceedings of the 12th Pacific Northwest Symposium on Water Pollution Research, Pacific Northwest Laboratory, U.S. Department of Health, Education and Welfare, 1963.

Moore, E.W. "Thermal Pollution of Streams," Industrial and Engineering Chemistry, Vol. 50, No. 4, Apr. 1958, pp. 87-A - 88A, Reprint No. 23, Division of Engineering and Applied Physics, Harvard University, Cambridge, Mass.

Neill, C.R.; Galay, V.J., Systematic Evaluation of River Regime, Journal Waterways and Harbor Div. Proceedings of ASCE, Paper No. 5083, Feb. 1967.

Norris, R. "Evaporation from Extensive Surfaces of Water Roughened by Waves", Royal Meteorological Society, Quarterly Journal, Vol. 74, No. 319, Jan. 1948, pp. 1-12.

"Nuclear Power Plant Proposal Raises Pollution Issues," Water Control News, Vol. 1, No. 1, May 16, 1966.

"Ohio River Pollution Control," House Document No. 266, Report of the U.S. Public Health Service, Part 2, 1944, p. 417.

Othmer, D.F., "Vapor Pressure as a Function of Temperature", Ind. Engr. Chem., 49, 125 (1957)

Parker, Frank L., "Eddy Diffusion in Reservoirs and Pipeline," Journal of the Hydraulics Division, ASCE, Vol. 87, No. HY3, Proc. Paper 2825, May 1961; with discussion by G.T. Orlob, Vol. 88, No. HY1, Proc. Paper 3044, Jan. 1962, p. 109.

Pickard, G.L., and Trites, R.W. "Freshwater Transport Determination from the Heat Budget with Application to British Columbia Inlets," Journal, Fisheries Research Board of Canada, Vol. 14, No. 4, 1957, pp. 605-616.

Picton, Walter L. "Water Use in the United States 1900-1975." Business Service Bulletin 136. Water and Sewerage Industry and Utilities Division, U.S. Dept. of Commerce, January 1956.

Preddy, W.S. and Webber, B. "Calculation of Pollution of Thames Estuary by Theory of Quantized Mixing," Air and Water Pollution, Vol. 7, W8, Oct. 1963, p. 829.

"Prevention of River Pollution, Appendix C: Discharge of Heated Liquids into Streams," Report of the River Pollution Sub-Committee of the Central Advisory Water Committee, Her Majesty's Stationery Office, London, 1949, pp. 69-76.

Pritchard, D.W. "Estuarine Circulation Patterns," Proc. Sep. No. 717, ASCE, Vol. 81, June 1955.

Pritchard, D.W., and Carter, H.H. "On The Prediction of the Distribution of Excess Temperature From A Heated Discharge in an Estuary." Feb. 1965, Johns-Hopkins University, Chesapeake Bay Institute.

Pruden, F.W., R.L. Wardlaw, D.C. Baxter and J.L. Orr, "A Study of Winter-time Heat Losses from a Water Surface and of Heat Conservation and Heat Addition to Combat Ice Formation in the St. Lawrence River." Nat. Res. Council Canada, Report MD-42, pp 56 1954.

"Proceedings, Conference on Physiological Aspects of Water Quality," Public Health Service, U.S. Dept. of Health, Education and Welfare, Wash. D.C. Sept. 8-9, 1960.

Raphael, Jermone, M. "Temperature Phenomena and Control in Reservoirs," Water Temperature, Influences, Effects and Control, Proceedings of the 12th Pacific Northwest Symposium on Water Pollution Research, Pacific Northwest Laboratory, U.S. Department of Health, Education and Welfare, 1963.

Raphael, J.M., 1962. "Prediction of Temperature in Rivers and Reservoirs", Proc. ASCE, 88: PO 2: 157-181 (Separate No. 3200).

Reimer, N., Combs, B.D., 1956. "Method of Evaluating Temperature in Lakes with Description of Thermal Characteristics of Convict Lake, California, U.S. Fish and Wildlife Service, Fish. Bull. 56 (105): 535-553.

"Report of Water Pollution Study, Mahoning River Basin," Ohio Dept. of Health, Oct. 1954.

Richards, R.T. "Circulating Water Systems of Steam Power Plants," Combustion, Vol. 29, No. 7, Jan. 1958, P. 45.

Richards, R.T., "Water Resources Planning - Its Influence on Thermal Station Design." ASCE Conference on Thermal Pollution, Oct. 1967.

Richardson, Burt, "Evaporation as a Function of Insolation," Transactions, ASCE, Vol. 95, 1931, pp. 996-1019.

Riley, James J. "The Heat Balance of Class "A" Evaporation Pan", Water Resources Research Center, Univ. of Arizona, Tucson, Arizona, Water Resources Research, P. 223, Vol. 2, No. 2, 2nd Quarter 1966.

Rimsha, V.A., and R.V. Donchenko, "The Investigation of Heat Loss from Free Water Surfaces in Winter-Time (in Russian)", Trudy Leningrad Gosud. Gidrol. Inst., 65, 54-83, 1957.

Rohwer, C., 1931. "Evaporation from Free Water Surfaces", U.S. Dept. of Agriculture, Technical Bulletin No. 271, p. 96.

Ross, F.F., "The Operation of Thermal Power Stations in Relation to Streams," Journal, Institute of Sewage Purification (1959) p. 16-26.

Ruggles, W.B. "The Reduction in Temperature of Condensing Water Reservoirs Due to Cooling Effect of Air and Evaporation," Transactions, American Society of Mechanical Engineers, Vol. 34, Paper No. 1357, 1912.

Saltzman, B. ed. "Selected Papers on the Theory of Thermal Convection," Dover Publications, New York, 1962.

Salzman, M. G., "Water Supply for Texas Steam Electric Stations," Journal of the Power Division, ASCE, Vol. 82, No. PO4, Proc. Paper 1044, Aug. 1956.

Sanderson, Albert E. Jr., "Comments Relating to the Proposed Discharge of Water of High Temperatures Upon the Natural Resources of the State of Maryland in the Potomac River near Dickenson, Montgomery County," by the Potomac Electric Power. Co., to the Game and Inland Fish Commission.

Saur, J. F. T., Anderson, E. R., 1956. "The Heat Budget of a Body of Water of Varying Volume, Limnol. Oceanog., 1 (4): 247-251.

Sayre, W. W., and A. R. Chamberlain, "Exploratory Study of Lateral Turbulent Diffusion at the Surface of an Alluvial C hannel", U. S. Geological Survey Circular 484, p. 18, 1964.

Scheidegger, Adrian E. "Statistical Description of River Networks." Water Resources Research, Vol. 2, No. 4, 4th Qtr., 1966, P. 785.

Schrader, T. "Thermal Conditions in Impounding Reservoirs, "Limn. Sch. Reihe, Vol. 5, No. 21, 1958, pp. 68-88; Sport Fisheries Abstracts, Vol. 5, No. 3, 1960.

Shetter, D. S., and Whalls, M. J. "Effect of Impoundment on Water Temperatures of Fuller Creek, Montmorency County, Michigan," Journal of Wildlife Management, Vol. 19, No. 1, 1955, pp. 47-54, Sport Fisheries Abstracts, Vol. 1, No. 4, 1956.

Simpson, R. W. "Urban Redevelopment and Thermal Discharge," Water and Sewage Works, Nov. 1960, pp. 448-449.

Slack, K. V., Clarke, F. E., 1965, "Patterns of Dissolved Oxygen in a Thermally Loaded Reach of the Susquehanna River, Pennsylvania, Prof. Paper, U. S. G. S. 525-C: 193-195.

Spangenberg, W. G., and Rowland, W. R. "Convective Circulation in Water Induced by Evaporative Cooling," The Physics of Fluids, Vol. 4, No. 6, June 1961.

Spencer, R. W., and Bruce, J. "Cooling Water for Steam Electric Stations on Tidewater," Journal of the Power Division, ASCE, Vol. 86, No. PO3, Proc. Paper 2503, June 1960.

Staff, Chem. Engr. Prog., "Effect of Water Temperature on Stream Re-aeration,"Chem. Engr., Prog. 56:33.

Stankiewicz, E. J., "Water Supply to Thermal Power Plants," Journal of the Power Division, ASCE, Vo. 84, No. PO6, Proc. Paper 1889, Dec. 1958.

"Steam-Electric Plant Construction Cost and Annual Production Expenses," Thirteenth Annual Supplement, 1960, Federal Power Commission, Wash. D. C. 1960.

Stoltenberger, D. H. and Sobel, M. J., 1965. "Effect of Temperature on The Deoxygenation of a Polluted Estuary." J. Water Poll. Control Fed. 37(12): 1705-1715.

Stolzenbach, K., "Modelling of Thermally Stratified Flow", Masters Thesis, M. I. T., Cambridge, Mass.

Strandberg, Carl H., "Analysis of Thermal Pollution from The Air," Proceedings, 17th Industrial Wastes Conference, at Purdue University, Lafayette, Ind., May 3, 1962.

Strandberg, Carl H., "Dispersion and Diffusion of Heated Coolant Water," Second Progress Report to the U. S. Public Health Service Division of Water Supply and Pollution Control, under Research Grant WP-181, Sept. 30, 1962.

"A Study of Convective Currents in Water," Technical News Bulletin No. 45, National Bureau of Standards, U. S. Dept. of Commerce, Wash. D. C. June 1961.

Sutton, O. G., "Convection in the Atmosphere Near the Ground," Royal Meteorlogical Society, Quarterly Journal, Vol. 74, No. 219, 1948, pp. 13-30.

Sutton, O. G., "Wind Structure and Evaporation in a Turbulent Atmosphere," Royal Society of London, Proceedings, Ser. A, vol. 146, No. 858, Oct. 1934. pp. 701-722.

Sverdrup, H., "On the Evaporation from the Oceans," Journal of Marine Research, Vol. 1, No. 1, 1937.

Sverdrup, H. U., "On the Ratio Between Heat Conduction from the Sea Surface and Heat Used for Evaporation," Boundary-Layer Problems in the Atmosphere and Ocean, New York Academy of Sciences, Annals, Vol. 44, art. 1, 29 May 1943, pp. 81-88.

Sylvester, Robert O., "Some Influences of Multi-Purpose Water Usage on Water Quality," 7th Technical Meeting of the International Union Cons. Nature and Natural Resources, Theme 1, No. 4, 1960, pp. 215-235; Sport Fisheries Abstracts, Vol. 5, No. 4, 1960.

Sylvester, Robert O., "Effects of Water Uses and Impoundments on Water Temperature," Water Temperature, Influences, Effects and Control, Proceedings of the 12th Pacific Northwest Conference on Water Pollution Research, Pacific Northwest Laboratory, U.S. Department of Health, Education and Welfare, 1963.

Sylvester, R.O. & Carlson, D.A., "Lower Columbia River Basic Water Quality Data Analysis for the Year 1960", Univ. of Wash., Dept. of Civil Engr. Oct. 1961.

Tabata, Susuma, "Heat Budget of the Water in the Vicinity of Triple Island, British Columbia," Journal Fisheries Research Board of Canada, Vol. 15, No. 3, 1958.

"Thermal Pollution of Water", Sport Fishing Institute, Jan-Feb. 1968, 719-13th Street, N.W., Washington, D.C. 20005.

Thom, H.C.S., "Discussion of the Heat Balance Method for the Determination of Evaporation from Water-Surfaces", by B. Holzman, American Geophysical Union, Transactions, Vol. 22, part 3, Aug. 1941, pp. 659-660.

Thomann, Robert V., "Recent Results from a Mathematical Model of Water Pollution Control in the Delaware Estuary", Water Resources Research, Vol. 1, No. 3, 1965, p. 349.

Thorne, R.F., "How to Predict Lake Cooling Action," Power, Vol. 95, Sept. 1951, p. 86.

Timofeyer, M.P. 1958, "On the Method of Computing the Temperature of Water Reservoirs", Meteorologlyai Gidrologiya, 12:3-9.

Trembley, F.J., 1960. Research Project on Effects of Condenser Discharge Water on Aquatic Life. I. Progress Report 1956-59, November 21, 1960. 1961. II Progress Report, 1960, April 21, 1961. Lehigh University Institute of Research, Bethlehem, Pa. Unpublished.

Truesdale, G.O., and K.G. Van Dyke, 1958. "Effect of Temperature on Aeration of Flowing Water". Water and Waste Treatment Journal 7: 9-11.

U.S. Fish & Wildlife Service, Report on Waste Heat Dissipation in Streams, Ponds & Reservoirs with application to the Duke Power Co. Keowee-Jocasse Development.

U.S. Senate Select Committee on National Water Resources, 1960a. Electric Power in Relation to the Nation's Water Resources, Committee Print No. 10, U.S. Gov't Printing Office, Washington, D.C.

U.S. Senate Select Committee on National Water Resources, 1960b. Water Supply and Demand, Committee Print No. 32, U.S. Gov't Printing Office, Washington, D.C.

Velz, C.J., "Deoxygenation and Reoxygenation", Trans. ASCE, 104, 1939.

Velz, C.J., "Factors Influencing Self Purification and Their Relation to Pollution Abatement", Sewage and Industrial Wastes, 19 July 1949.

Velz, C.J. and Gannon, J.J., "Forecasting Heat Loss in Ponds and Streams," Journal Water Pollution Control Federation, 32 (1960) 392-417.

Velz, C.J., and Gannon, J.J., "Low Flow Characteristics of Streams," Ohio State University Studies in Engineering Series, Vol. 22, No. 4, 1953, p. 138.

Von Lossberg, L.G. "Cooling Water Discharge," presented at the 39th Annual Meeting of the Maryland-Delaware Water and Pollution Control Association, Rehoboth, Del., June 9, 1966.

Ward, J.C., "Annual Variation of Stream Water Temperature," Journal of the Sanitary Engineering Division, ASCE, Vol. 89, No. SA6, Proc. Paper 3710, Dec. 1963.

"Water Requirements of Electric Utility Steam-Electric Plants in 1959," Federal Power Commission, Washington, D.C.

"Water Temperature, Influences, Effects, and Control, Proceedings of the 12th Pacific Northwest Symposium on Water Pollution Research, Pacific Northwest Laboratory, Public Health Service, U.S. Dept. of Health, Education and Welfare, 1963.

"Water Temperature Studies for 1958-59 Middle Snake River Drainage", Dept. of the Interior, Fish and Wildlife Service, Bur. Comm. Fisheries, 1960.

Wiebe, A.H., 1940, "The Effect of Density Currents Upon the Vertical Distribution of Temperature and Dissolved Oxygen in Norris Reservoir", J. Tenn. Acad. Sci. 15 (3): 301-308.

Woodcock, A.H. 1941. "Surface Cooling and Streaming in Shallow Fresh and Salt Water." J. Mar. Res. 4 (2): 153-160

Woodward, D.R. "Availability of Water in the United States with Special Reference to Industrial Needs by 1980", Thesis No. 143, Industrial College of the Armed Forces, April 1957.

Woodward, R.L. and LeBosquet, M. "Effect of Reservoir Operation on Stream Water Quality," Public Health Reports, Vol. 64, 1949, p. 1223.

Wurtz, C.B. "Is Heat a New Pollution Threat?" Wastes Engineering, Vol. 32, No. 12, 1961, pp. 684 et. seq.

Yih, Chia-shun, Dynamics of Nonhomogeneous Fluids, The MacMillan Co., New York, 1965.

Zeller, Robert, "Summary of Current Theories and Studies Relating to Temperature Prediction," Water Temperature, Influences, Effects and Control, Proceedings of the 12th Pacific Northwest Symposium on Water Pollution Research, Pacific Northwest Laboratory, U.S. Department of Health, Education and Welfare, 1963.